Electroactive Material Based Technologies for In-situ Planetary Exploration and Astrobiology

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NDEAA

Nondestructive Evaluation and Advanced Actuators Technologies

The JPL's Nondestructive Evaluation and Advanced Actuators (NDEAA) Technologies lab was established by Dr. Yoseph Bar-Cohen in May 1991 and it is part of his JPL's Advanced Technologies Group. The Group members are Dr. Jack B. Aldrich (Caltech Postdoc Scholar), Dr. Mircea Badescu, Dr. Xiaoqi Bao, Dr. Zensheu Chang, Ayoola Olorunsola and , Dr. Stewart Sherrit. Other scientists that are working in his NDEAA Lab include Dr. Shyh-Shiuh Lih , and Jay (Jiunnjenq) J. Wu . The NDEAA lab is one of the JPL Unique Facilities and it is involved with innovative research and development (R&D) for space applications and technology transfer to other fields. The topics of R&D include novel actuators (mostly using electroactive ceramics and polymers), transducers, sensors, robotic mechanisms and NDE methods. The group conducts analytical modeling, mechanisms development, performance testing and characterization as well as analysis that involve mechanical, electrical, magnetic and thermal parameters and interactions. Between Jan. 1, 2000 and Jul. 2, 2001, this NDEAA webhub had 1,000,007 (crossed the one million) total hits with 87,082 unique hits and by Sept. 3, 2001 it crossed the one hundred thousand (100,006) unique hits. The highest hits per day was recorded on March 9, 2005, where 9063 total hits and 3626 unique hits were recorded. This lab has been the subject of many articles in the news media. **The NDEAA lab is involved with a broad range of R&D topics as described in the following clickable icons. The photos of the NDEAA members are clickable to their biography**

Dr. Y. Bar-Cohen, Supervisor, Advanced Tech. Group & Senior Research Scientist | Dr. Jack Aldrich | Dr. Mircea Badescu | Dr. Xiaoqi Bao | Dr. Zensheu Chang | Dr. Shyh-Shiuh Lih | Ayoola K Olorunsola | Dr. Stewart Sherrit | Jay (Jiunnjenq) J. Wu

The developed mechanisms are driven by elastic waves, mechanical vibrations and/or electroactive materials. Examples of these mechanisms include ultrasonic and surface acoustic wave motors and piezoelectric pumps that are driven by traveling flexural waves. Recently, an ultrasonic/sonic driller/corer (USDC) was developed and shown to have enormous potential for sampling, deep drilling, probing, sensing and in situ analysis making it a Lab-on-a-Drill. In parallel, electroactive polymers are being investigated for use as actuators (artificial muscles). Other technologies that are being explored include Haptic interfaces for robotics and Human Muscle Enhancers -- high power ultrasound for medical treatment, ferroelectric source that generates various radiations and charged particles, biomimetic technologies and geophysical probing using elastic waves. In addition to planetary applications, these devices and mechanisms have potential terrestrial applications for medical, commercial, and others. These efforts involve technical cooperation with scientists and engineers at various universities, research institutes, medical centers and industry in the USA and internationally. Further, the Nov. 2001 issue of the NASA Tech Briefs covered Dr. Bar-Cohen and NDEAA in a "Who's Who in NASA" article.

R&D focus areas at the NDEAA Lab

- The NDE and Advanced Actuators (NDEAA) lab is part of the Advanced Technologies Group.
- It is responsible for developing mechanisms and devices that are driven by electroactive materials.
- The topics involve time dependent mechanical vibrations and/or elastic waves as follows:

	Small amplitude	Large amplitude
Low frequency (KHz)	Subsurface probing	Actuation
High frequency (MHz)	NDE & diagnostics	Medical treatment

Introduction

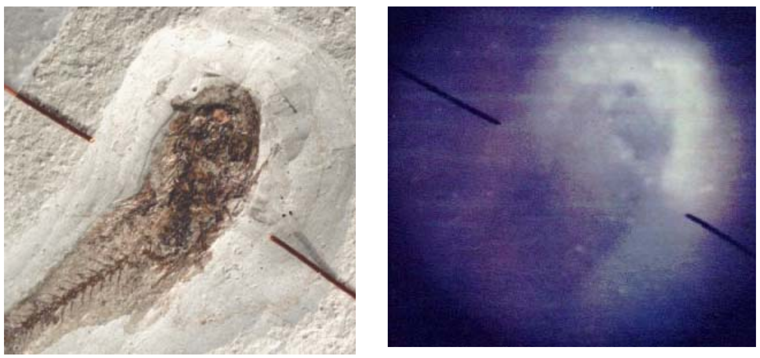
- The Nondestructive Evaluation and Advanced Actuators (NDEAA) Lab was established in 1991.
- Initially it supported NDE requirements where both research, development, pre-flight and flight hardware tests were made.
- Today, the lab conducts R&D and other activity addressing challenges related to sample acquisition, handling and in-situ analysis.
  - This involves analytical modeling, experimental tests and corroboration, material characterization
  - device and mechanisms design, construction and demonstration.
- The electroactive materials include mostly piezoelectric ceramics and electroactive polymers (EAP).
  - The developed piezoelectric based devices and mechanisms include ultrasonic motors, piezopump, USDC, Gopher, URAT, Ferrosource and many others.
  - Electroactive polymers were used to demonstrate a gripper, wiper, lifter and a haptic interface.
- This effort is multidisciplinary requiring expertise that are complemented by cooperation with researchers and engineers in the USA and internationally.
- Some of the developed innovations have been inspired by nature leading to biomimetic devices and techniques.

Piezoelectrics and Ferroelectrics

- **Ferrosource** – Generating multiple radiations from a single disc.
- **USM** – Compact motor that has high torque density, is non-backdrivable
- **Piezopump** – a peristaltic pump with no physically moving parts.
- **Wireless power feedthru** – transfer electric power and signals thru solid walls.
- **FMPUL** – Generate cavitation in confined zone for blood clot lysing
- **USDC** – subsurface penetration, probing and sampling using minimal axial load

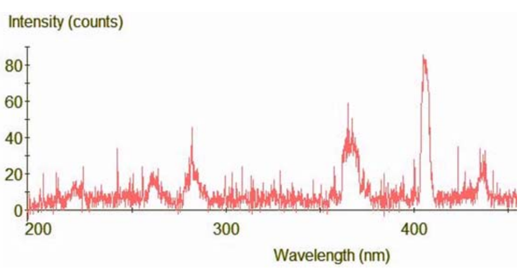
Ferrosource enabling planetary compact multi-functional analytical instruments

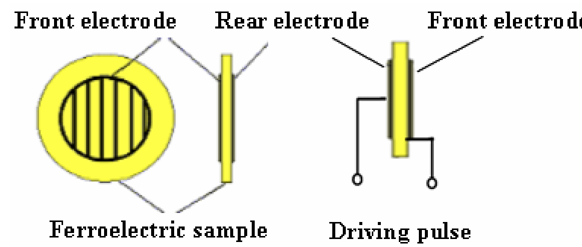
- A novel ferroelectric-based source was developed that emits multiple types of radiation including ion and electron beams, X-ray, visible light and UV.
- This source enabled a new generation of multifunctional analytical instruments that are compact, low power, and low mass.
- The emitted radiation types are used or planned to be used in future NASA missions to perform chemistry/mineralogical analysis, identify biological signatures as well as detect water and other resources.

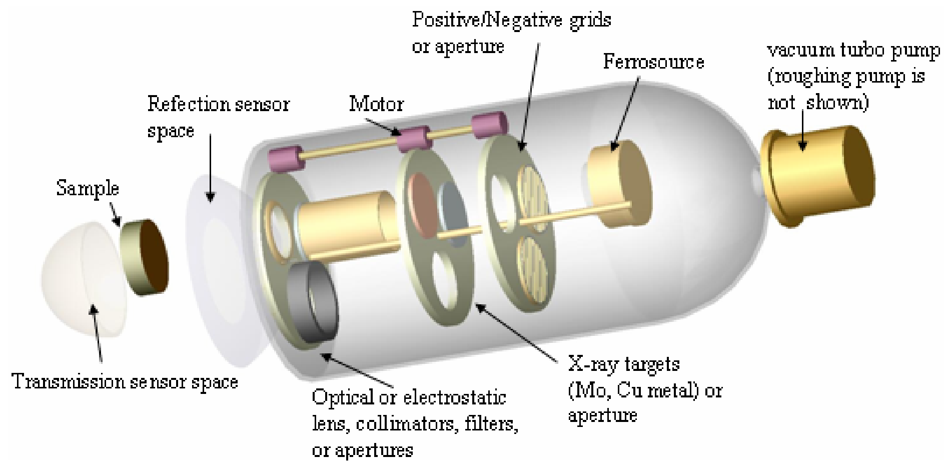


Fish fossil (left) and its radiograph (right) using the emitted X-rays

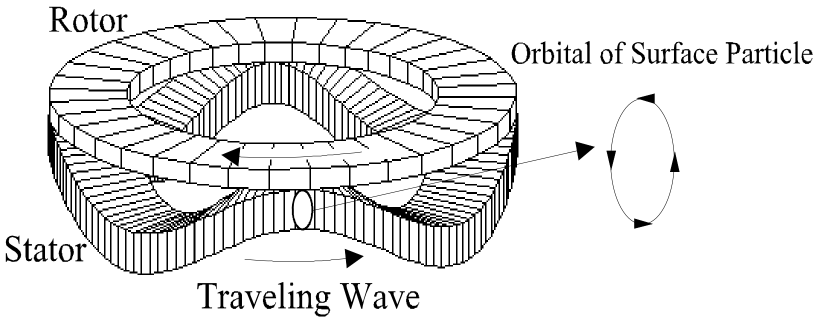
Visible light and UV

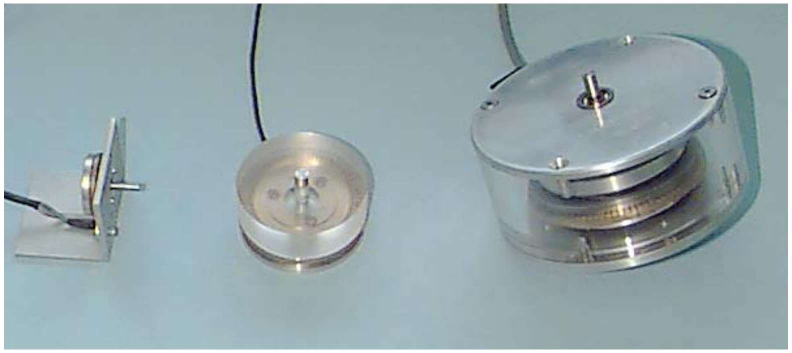






Ultrasonic motors (USM)

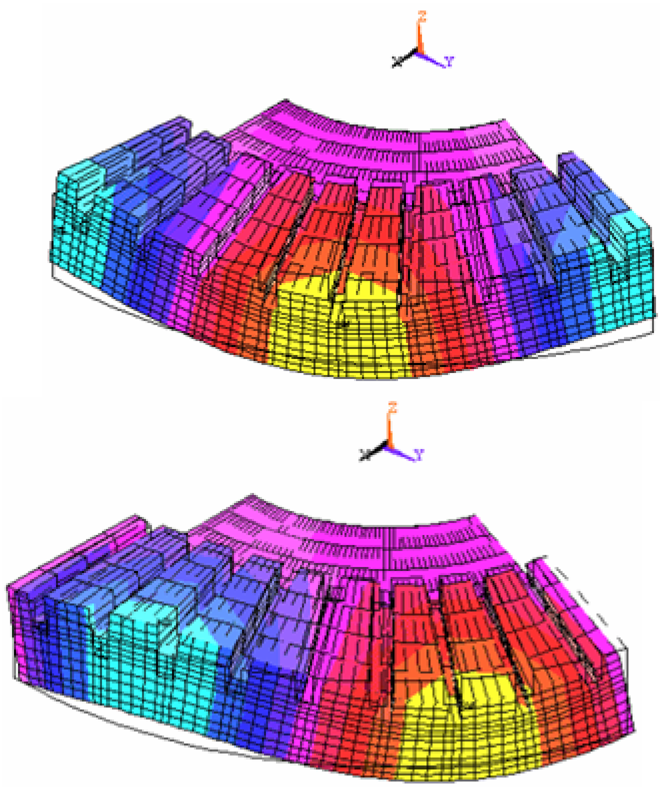




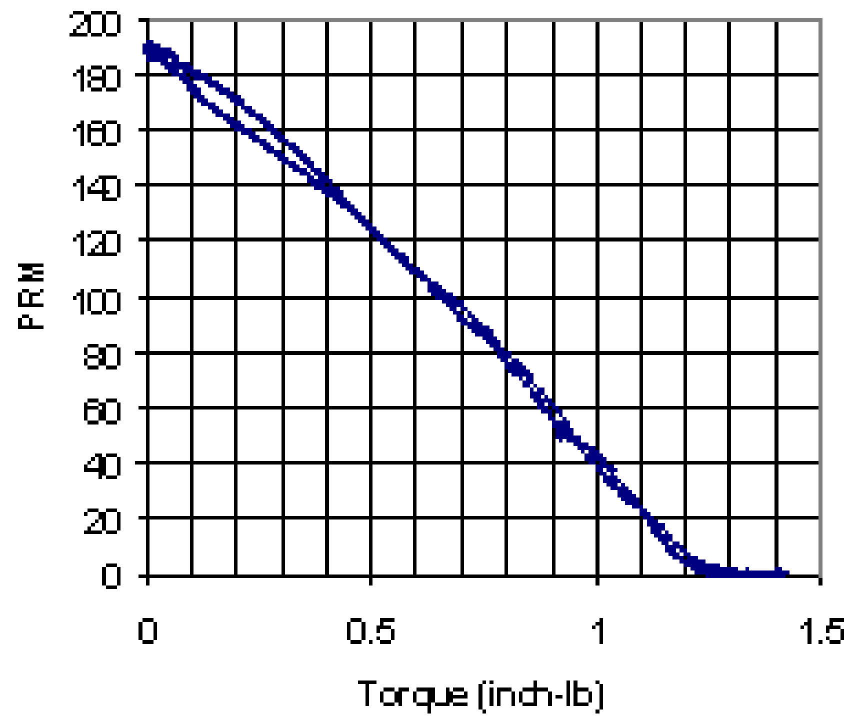
Ultrasonic motors are driven by traveling flexure waves generated via sequentially-poled segments on a piezoelectric disc. The advantages are:

- Direct drive in low speed
- Order of magnitude higher torque density than electromagnetic motors
- Unique configurations: Pancake and annular shape for electronic packaging
- Inherently non-backdrivable (self braking)
- Not affected by magnetic field or radiation

USM 3D analysis and Cryovac response



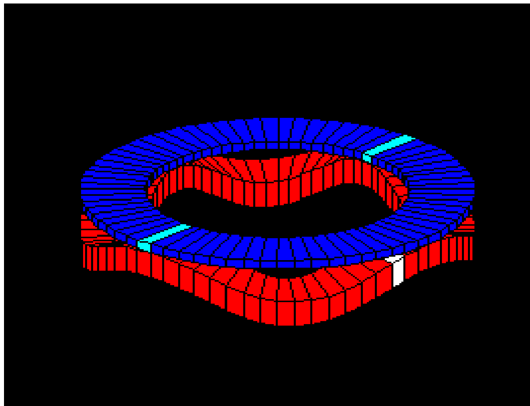
Detailed 3D analysis of USM using ANSYS FEM

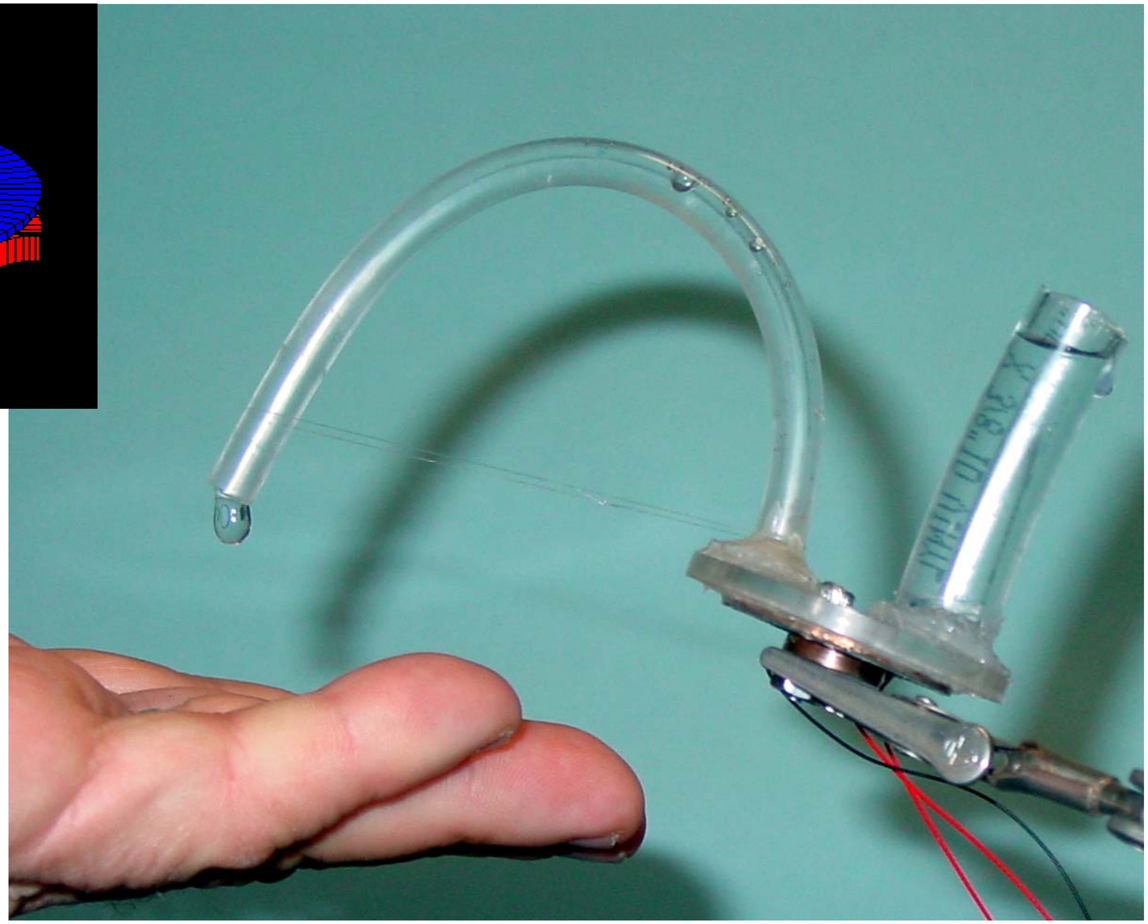


Torque-speed performance of a JPL/QMI USM subjected to -150ºC and 16 mTorr (lasted 336 hours)

Piezopump

Traveling ultrasonic waves allow peristaltic pumping of liquids

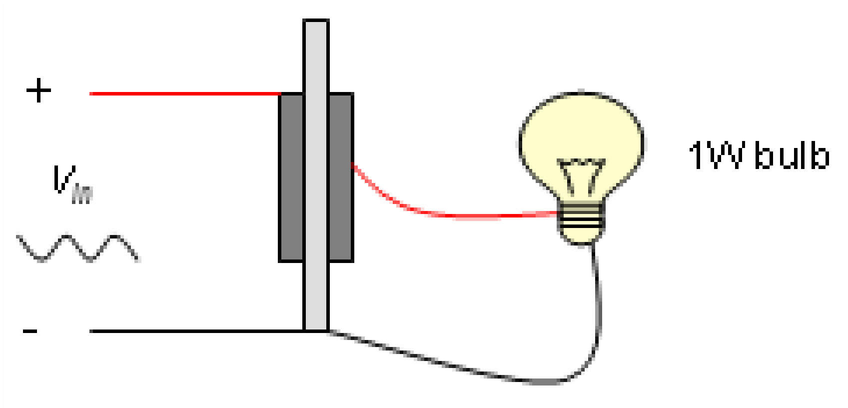


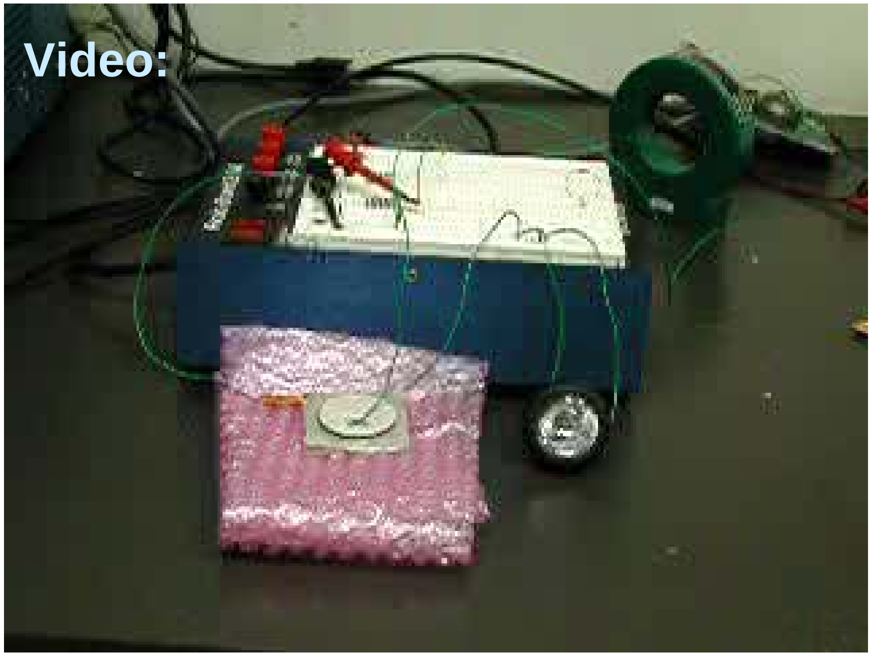


http://ndeaa.jpl.nasa.gov/nasa-nde/pump/piezopump.html

Power Transmission Demonstration

- Using piezoelectric disks, power is transferred thru a wall by converting an electrical signal to ultrasound, which is transmitted thru the desired wall.
- Using another piezoelectric disk as a receiver the transmitted ultrasonic signal is received on the other side of the wall and converted to an electric signal.
- This signal can be used for powering sensors and systems, charging battery, as well as for communications.

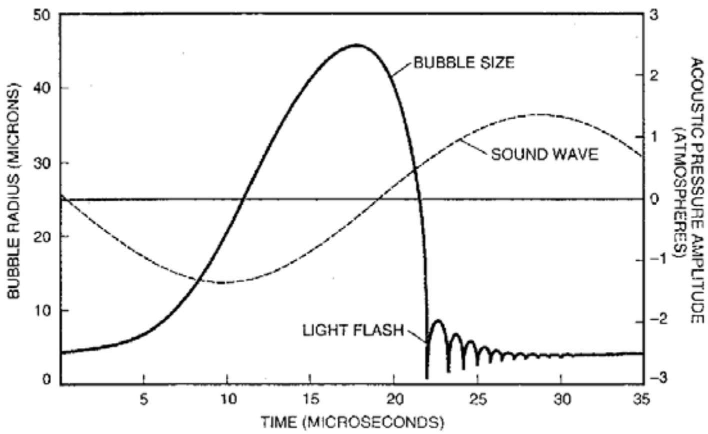


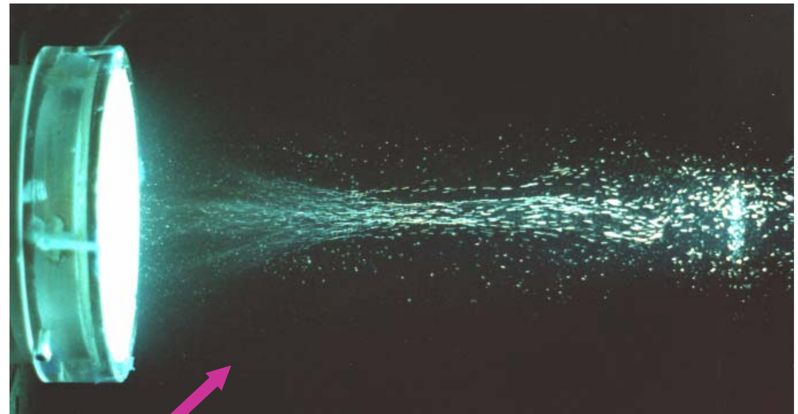


- Developed under funding from the Mars Sample Return (MSR) program
- Objective: Test potential leak thru a hermetically sealed container that will be filled with a sample from Mars for return to earth

High Power Ultrasound

Frequency Modulated high Power Ultrasonic (FMPUL) method

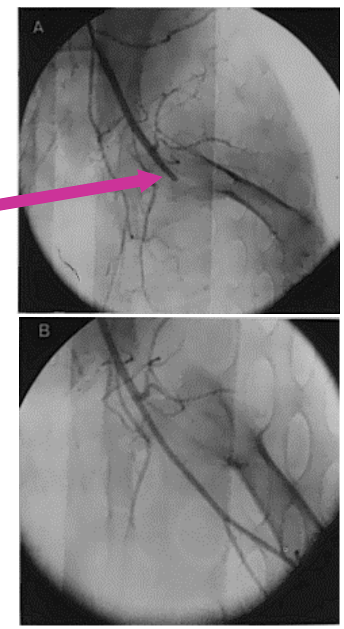




Flash photography dark-field view of cavitations formed in water using high power ultrasound

Angiographic example of the effect of through-the-skin ultrasound on the left leg artery of a rabbit.

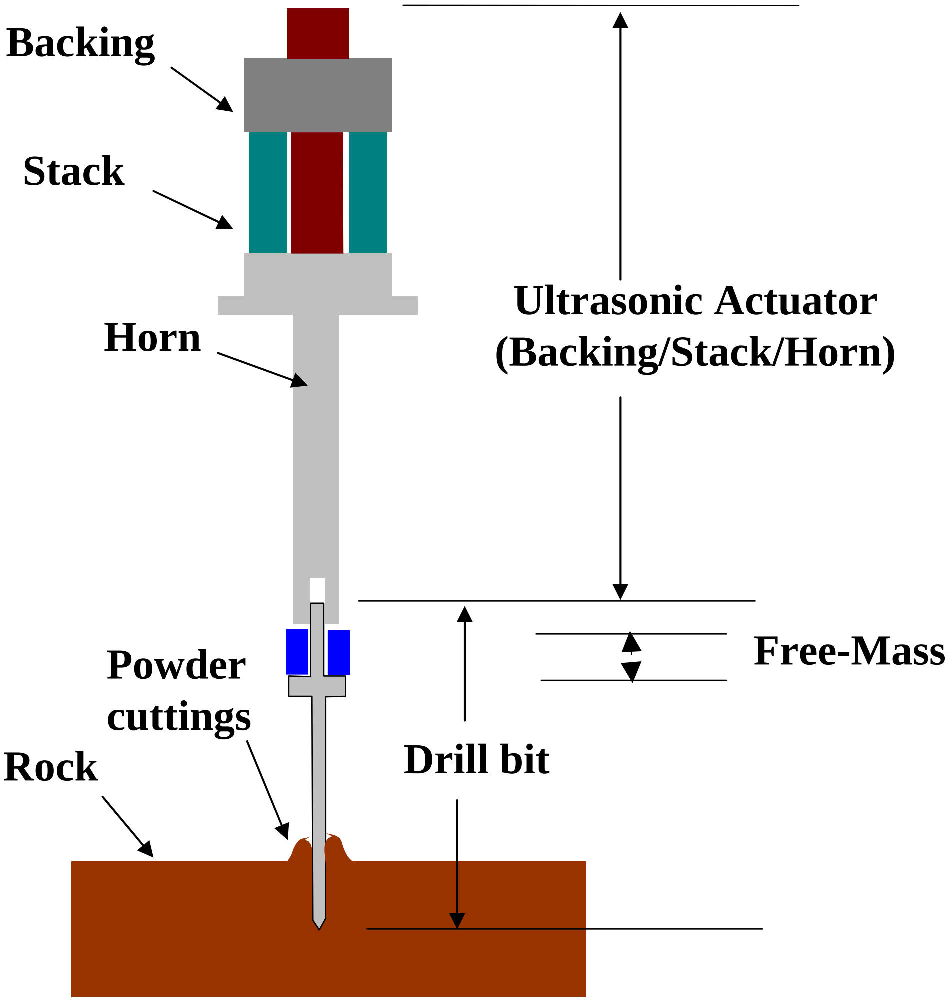
Blocked artery



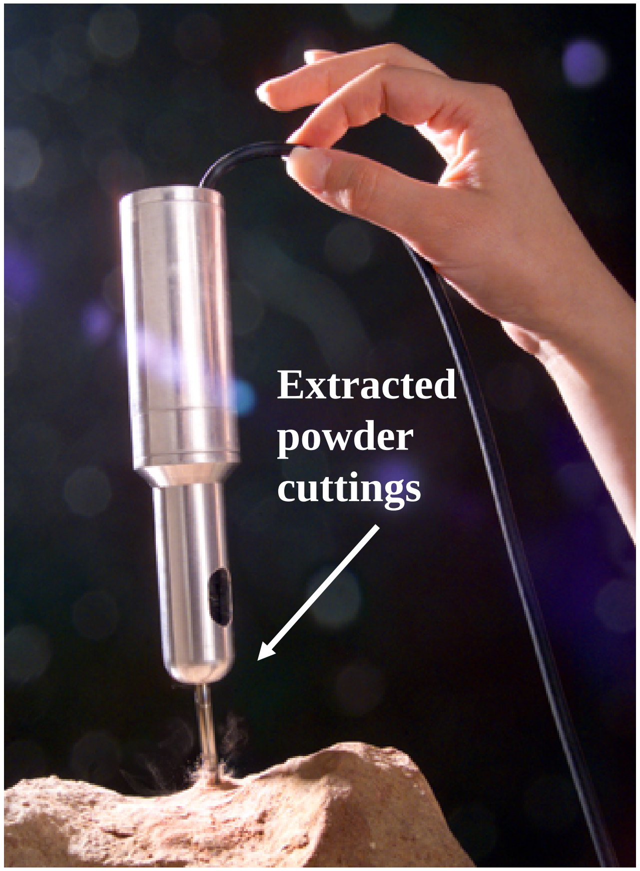
Recovered artery after 30 minutes of treatment

Joint development by JPL, QMI and Cedars-Sinai Medical Center

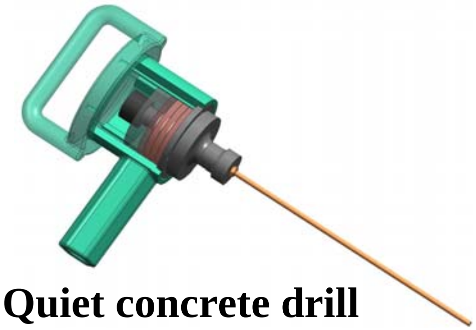
Ultrasonic/Sonic Driller/Corer (USDC)



2000 R&D 100 award



Applications of the USDC



Quiet concrete drill

Powdered cuttings sampler

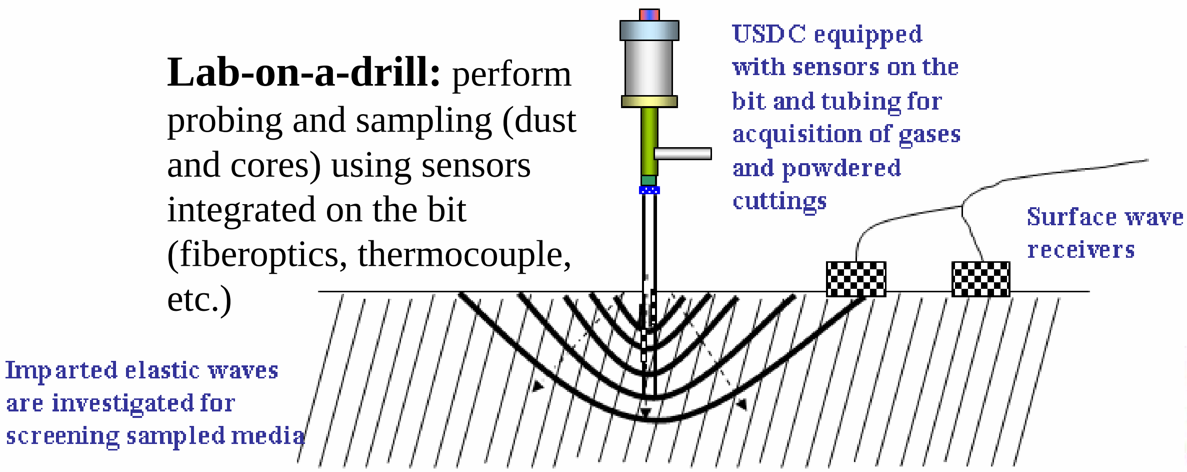
2000 R&D 100 award

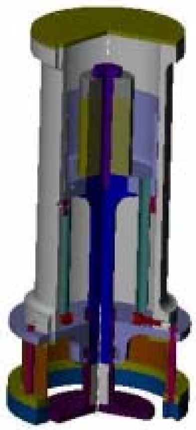
Simple feasibility tests was made operating the USDC from the Sojourner and the FIDO robotic arm

Ultrasonic Gopher for deep drilling

Proto-flight unit

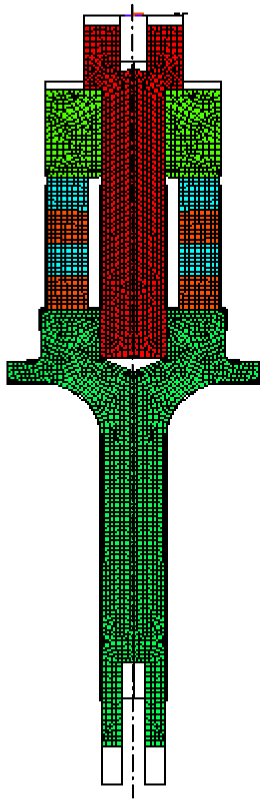
Lab-on-a-drill: perform probing and sampling (dust and cores) using sensors integrated on the bit (fiberoptics, thermocouple, etc.)

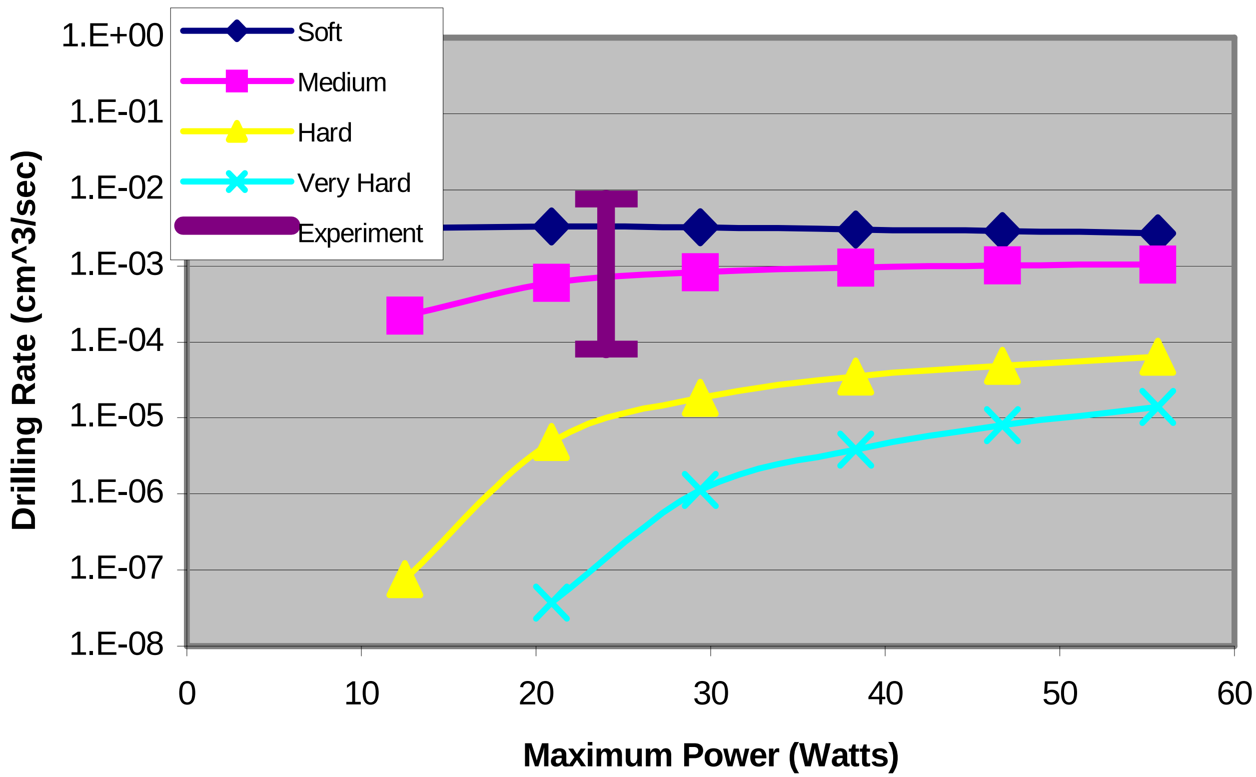




Ultrasonic Rock Abrasion Tool (**URAT**)

Drilling rate for different maximum power

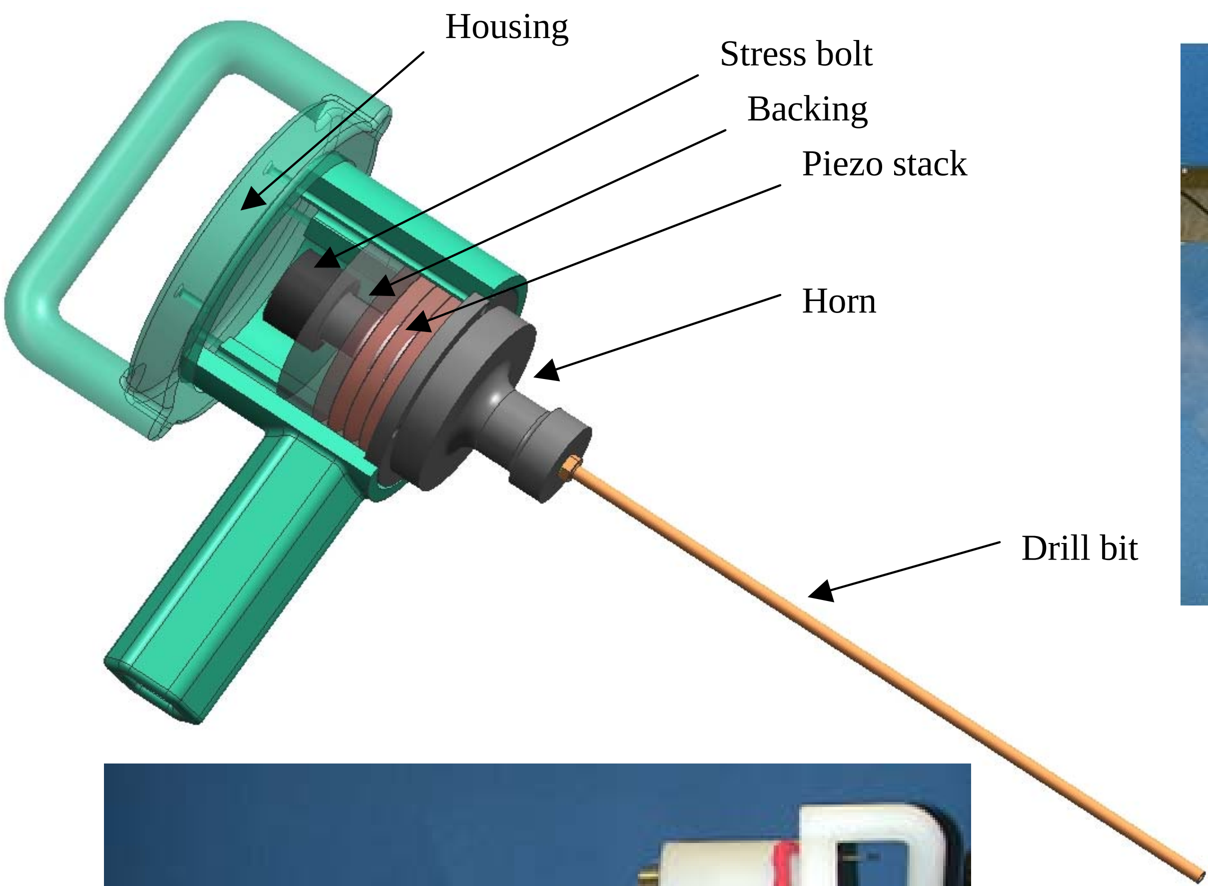


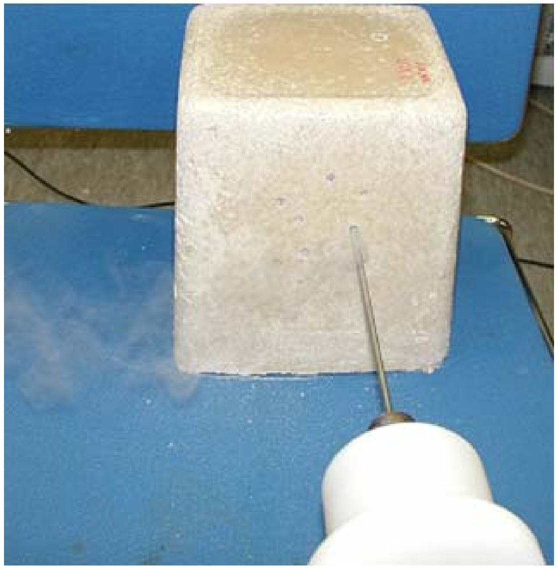


The average power is maintained at 10 watts by duty cycling the power supply

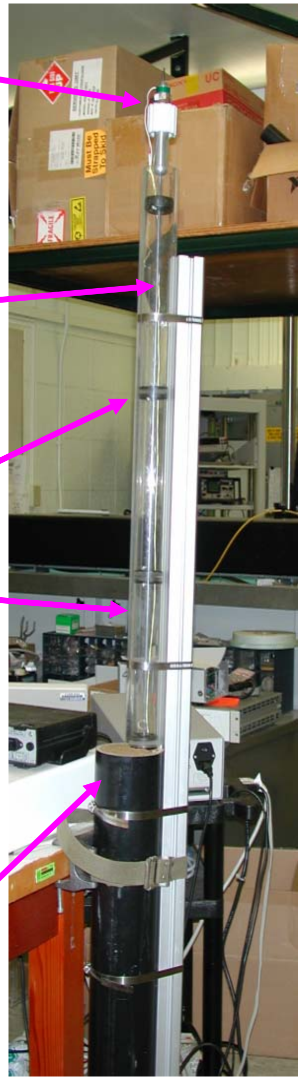
Note: The range described by the error bar was determined experimentally from a variety of rock samples.

Ultrasonic drill for quite drilling of concrete





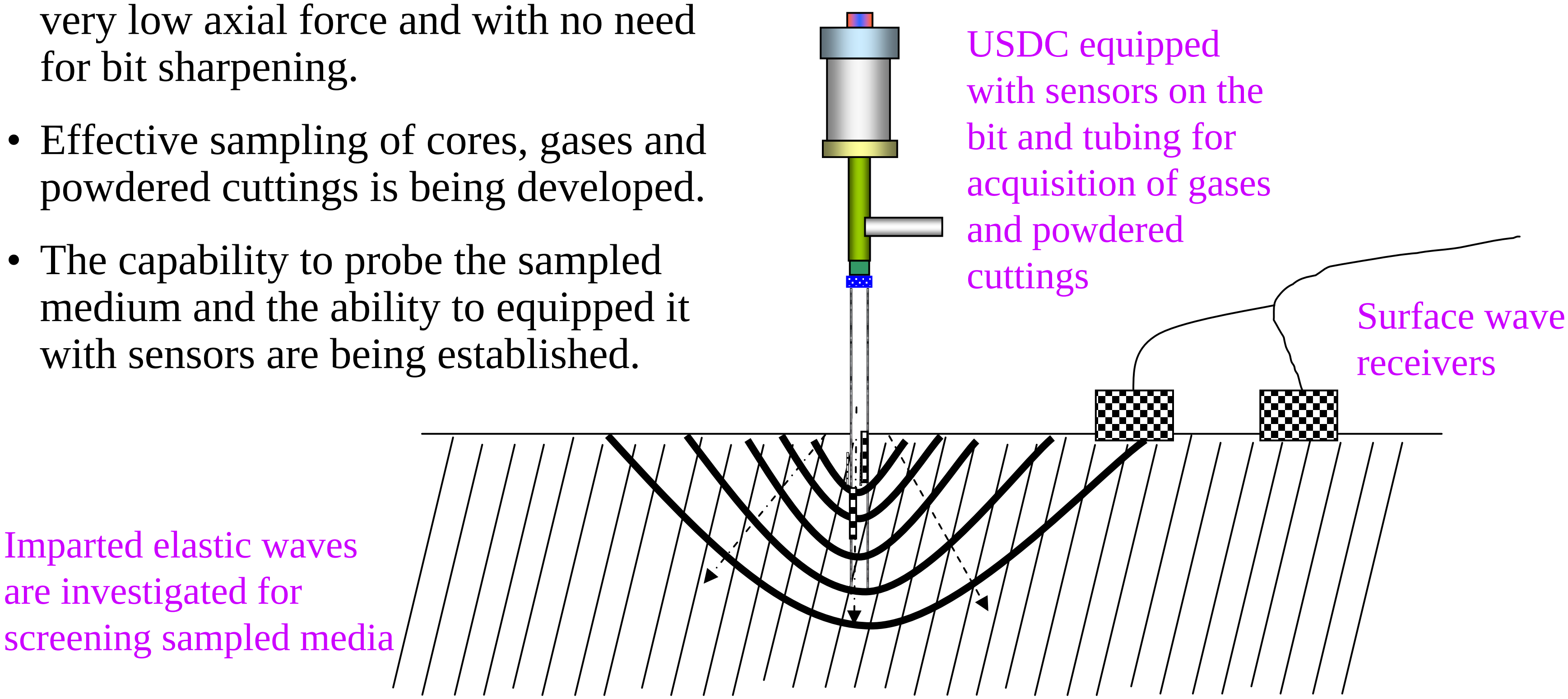
Soil penetrator and test bed



- Using 7 lb preload at ~70W and 20% duty cycled power, we reached a depth of 3-ft (~90-cm) in 30-40min.
- Since we used duty cycling the net drilling time is only about 6-8 minutes.

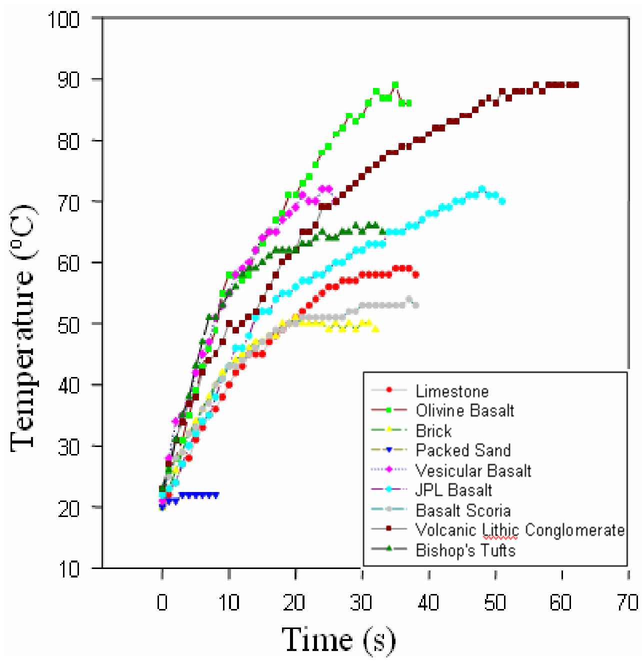
The Ultrasonic/Sonic Driller/Corer (USDC) as a probing, sampling and sensing system

- The USDC was demonstrated to core samples from rocks that range in hardness from soft to very hard using very low axial force and with no need for bit sharpening.
- Effective sampling of cores, gases and powdered cuttings is being developed.
- The capability to probe the sampled medium and the ability to equipped it with sensors are being established.



Bit Temperature measurements

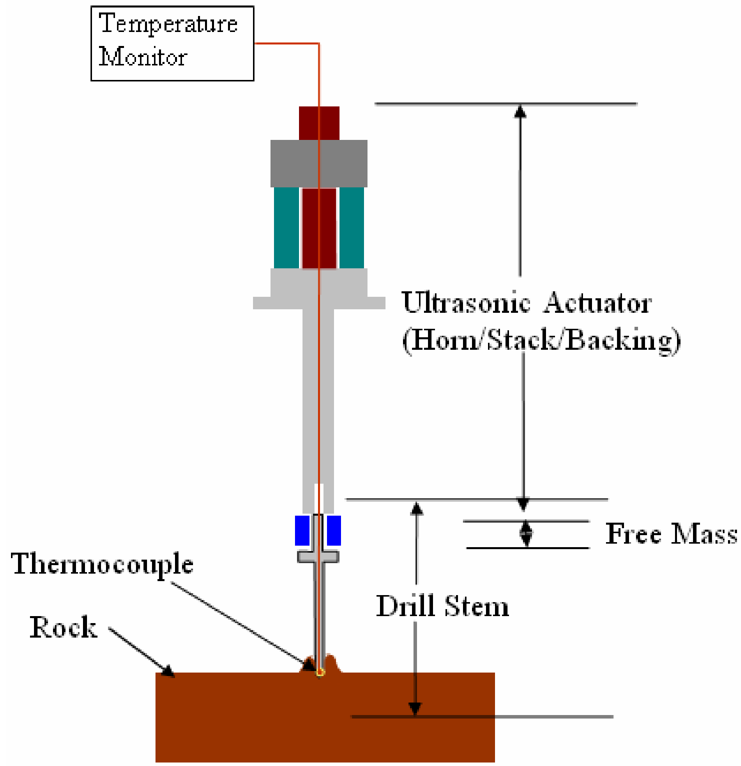
A thermocouple was integrated into the USDC bit to allow real time monitoring the temperature during drilling.



Temperature rate of rise and maxima as a function of time for drilling variety of media

Power < 40 watts

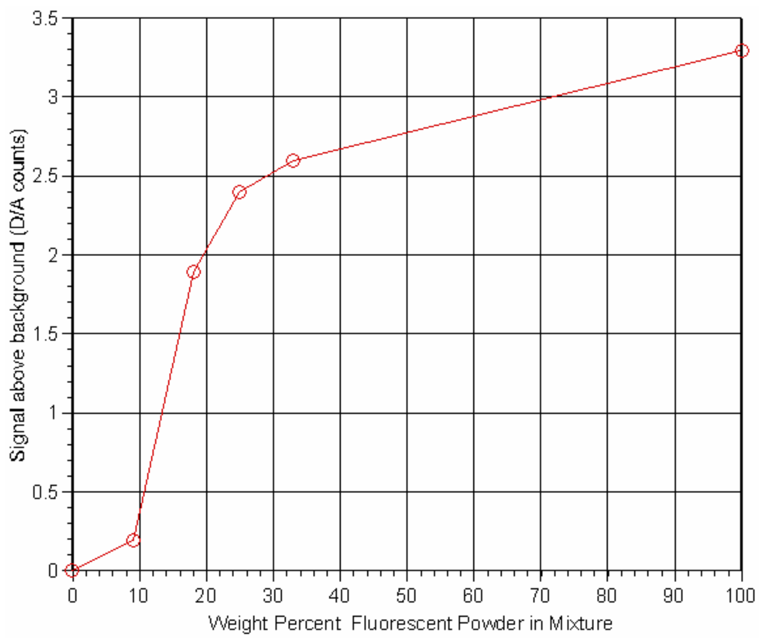
Bit diameter = 3.6 mm



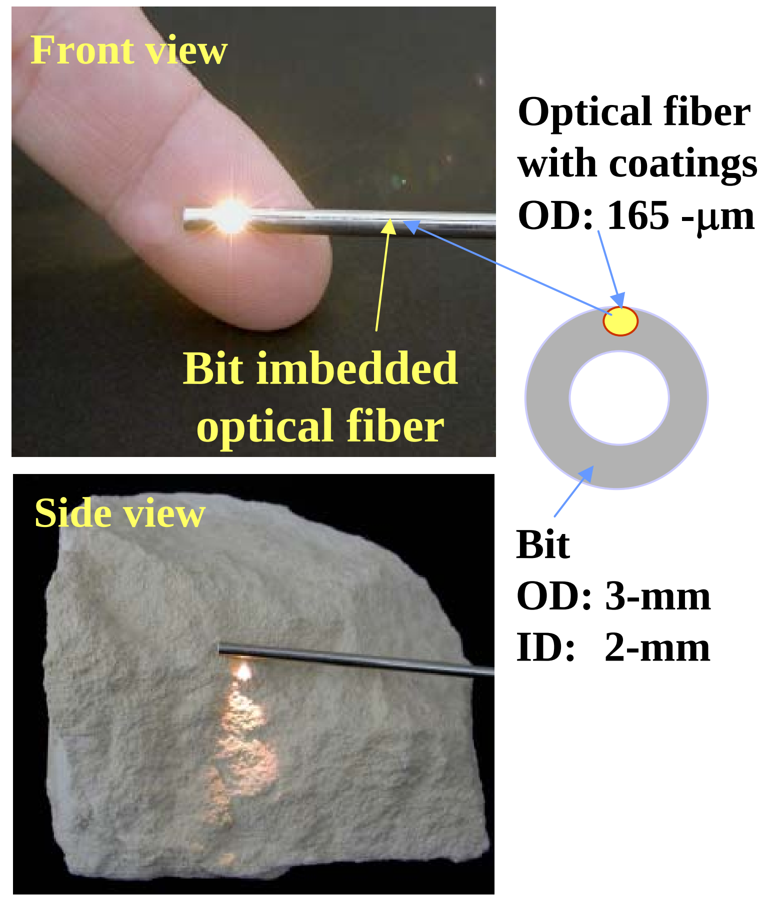
Experimental Setup

Integrated fiberoptics and measured reflectivity

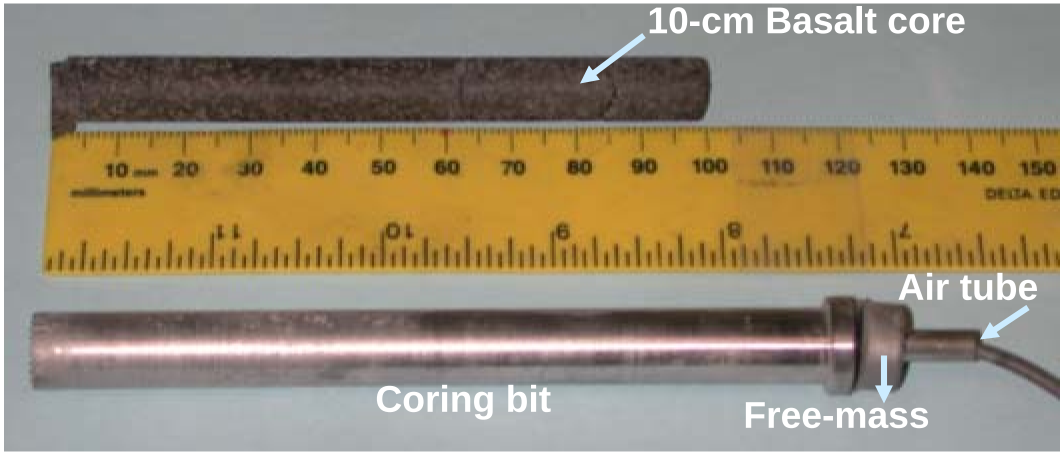
Preliminary study jointly with Research International, Inc

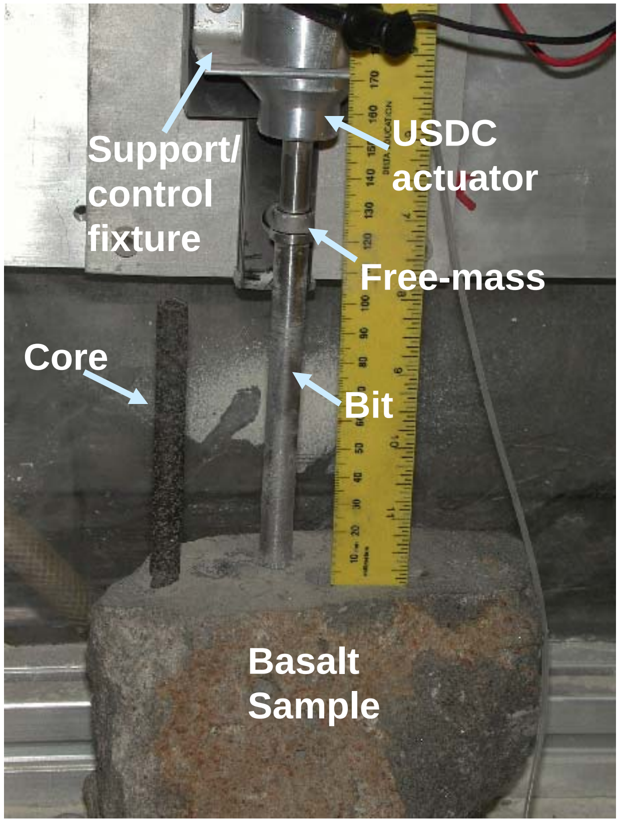


Differential response in the range of 545nm and 700nm



Coring basalt via the USDC

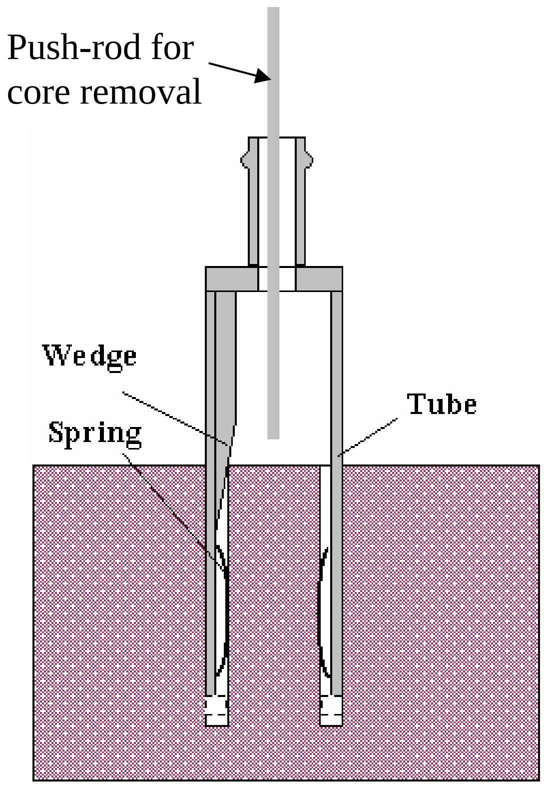




Coring set-up

USDC Core Breaking/Holding/Extracting

All-in-one bit using an internal wedge and side springs



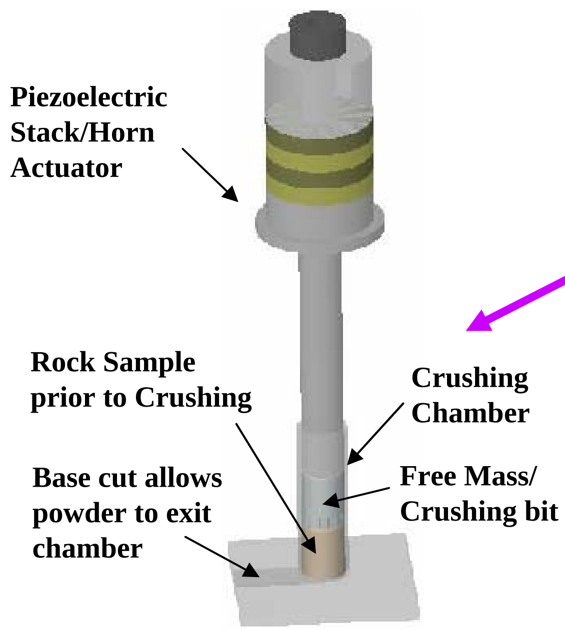
Retaining spring and a grabbed core

Two created cores (out of two attempts)

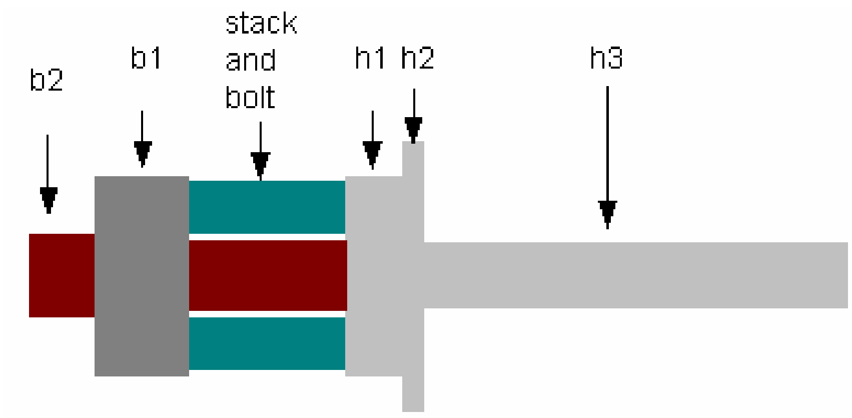
Powdered Cuttings

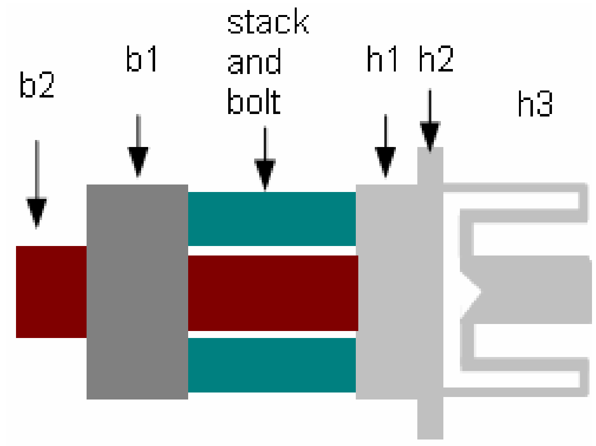
USDC crusher

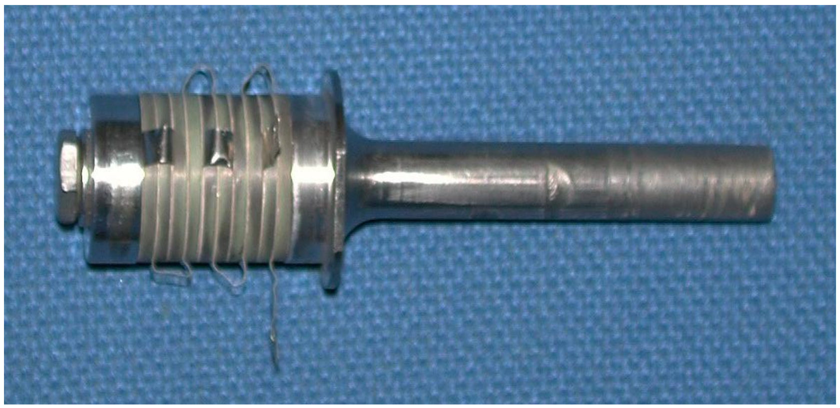
- The USDC is used as a rock crushing, milling, and powdering device.
- Its actuator harmonic motion creates a series of low frequency impacts that grind the sample into powder within a short time period.
- A crushing chamber confines the free-mass to movement in one direction only leading to a very efficient milling.
- The grinding effect can be enhanced by making a free-mass with teeth on its interface with the sample.



Stepped and folded horns

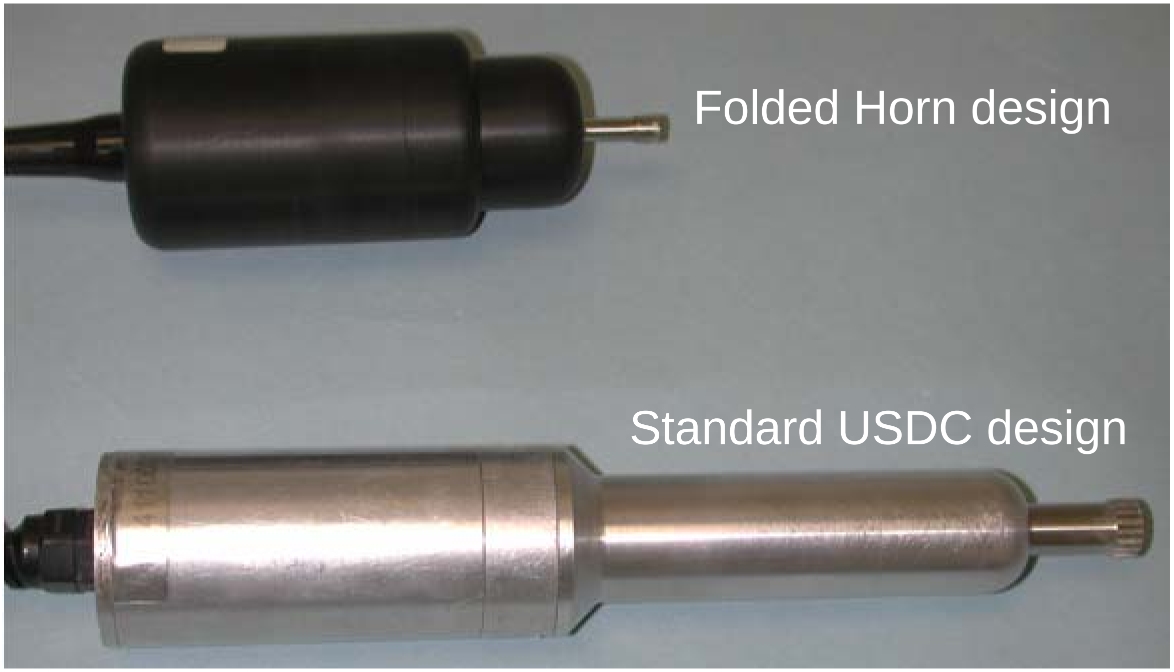


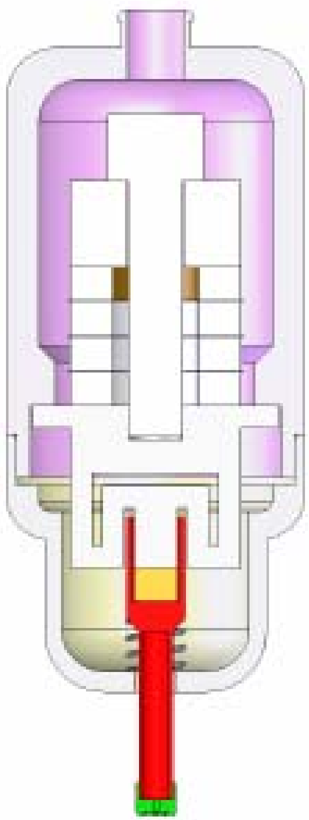




Dimensions reduction

- Using a folded horn the length of the powdered cuttings sampler was significantly reduced.
- A novel salt-shaker design was implemented into the bit configuration.





The Salt-Shaker design

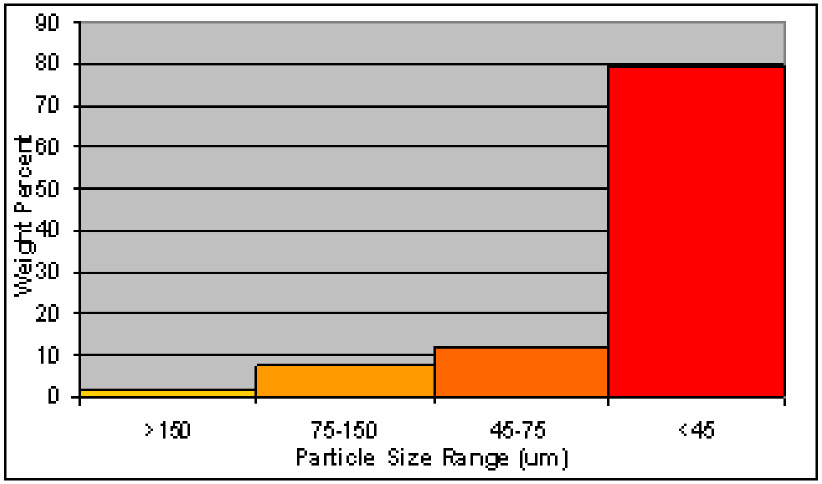
- A bit with conical holes (having their large diameter section facing down) was designed to acquire powdered cuttings.
- A reservoir was allocated inside the hollow bit for the accumulation of the powder.
- At the caching location, the powder is removed by activating the drill similar to a salt-shaker

A view of the bit cutting edge

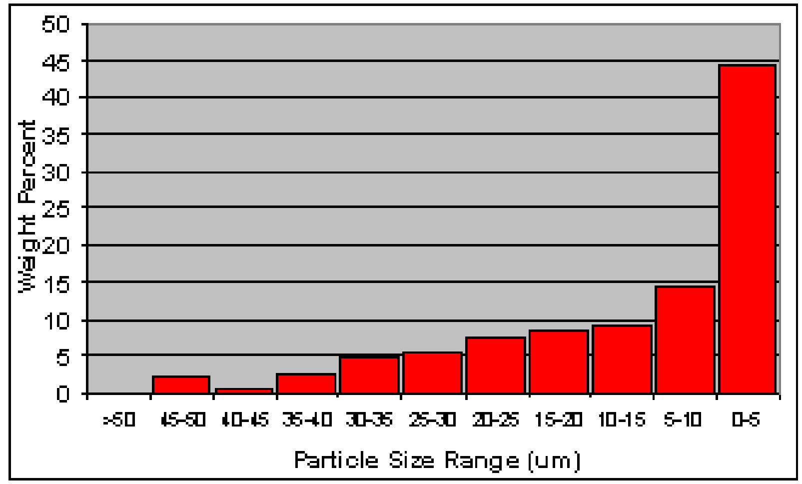
Sampled powder

The sampler in action drilling limestone and accumulating powdered cuttings inside the bit

CHEMIN Sample #1 – Chinle Sandstone



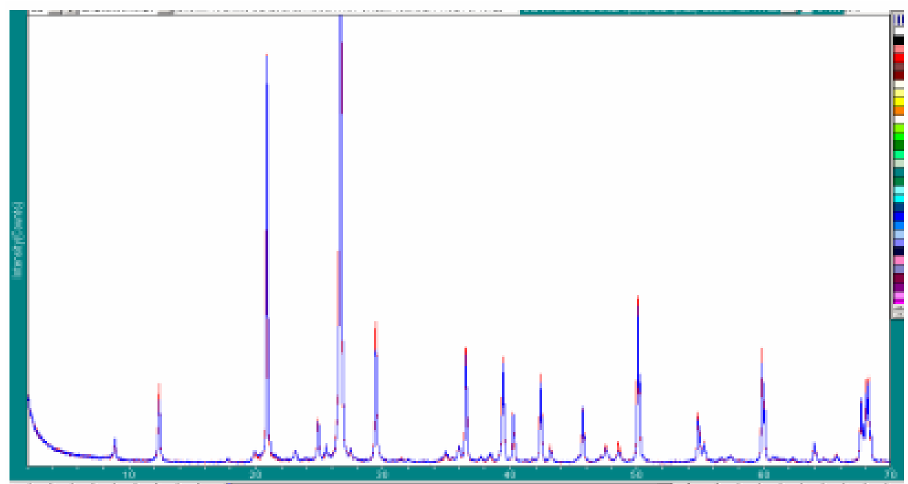
Size fractions obtained during wet sieving



Particle size distribution of the <45µm powder obtained using a Horiba CAPA-500 particle size distribution analyzer.

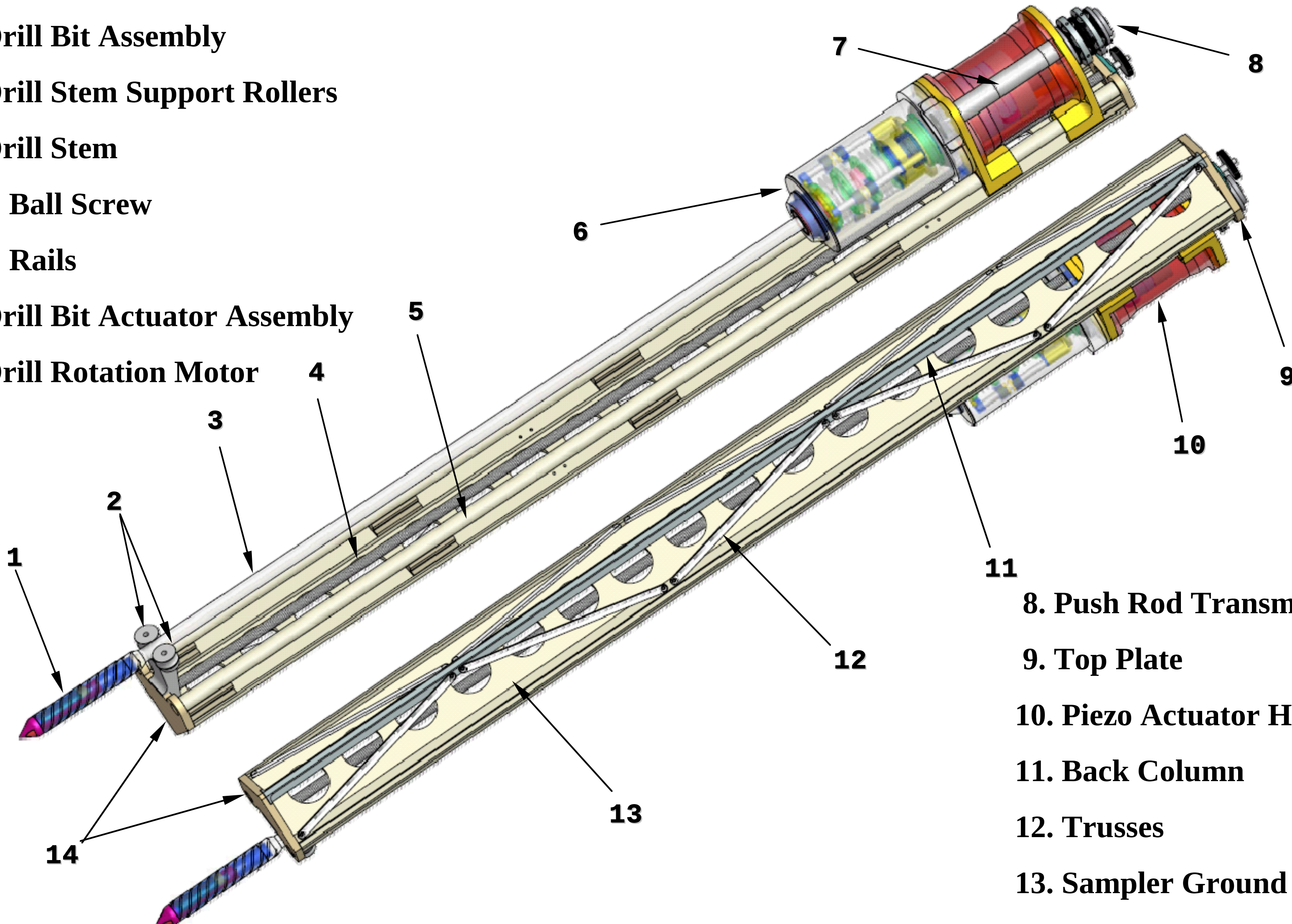
LANL's Lab XRD patterns of the <45 µ m USDC powder (blue) compared to the Retsch milled <5 µ m powder (red).

Note: The patterns compared extremely well.



USDC design of an all-in-one-bit for 0.5m deep drilling (with HBR)

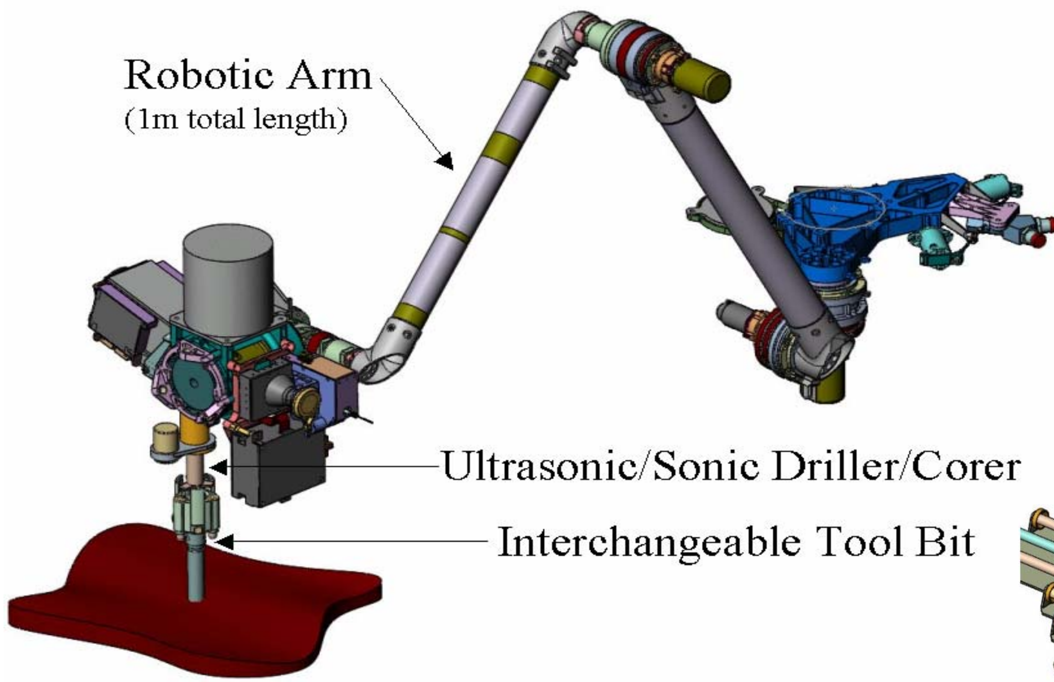
1. Drill Bit Assembly
2. Drill Stem Support Rollers
3. Drill Stem
4. Z Ball Screw
5. Z Rails
6. Drill Bit Actuator Assembly
7. Drill Rotation Motor

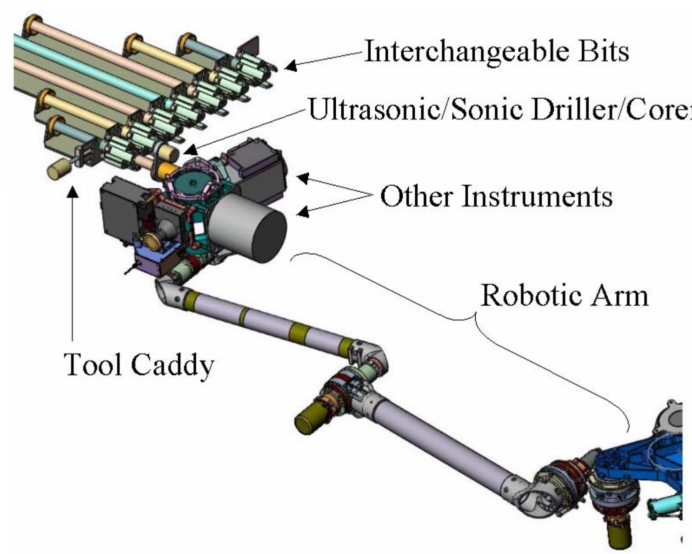


8. Push Rod Transmission
9. Top Plate
10. Piezo Actuator Housing
11. Back Column
12. Trusses
13. Sampler Ground Plate
14. Bottom Plate

Ref: Honeybee Robotics's drawing

USDC with interchangeable bit system (with ASI)

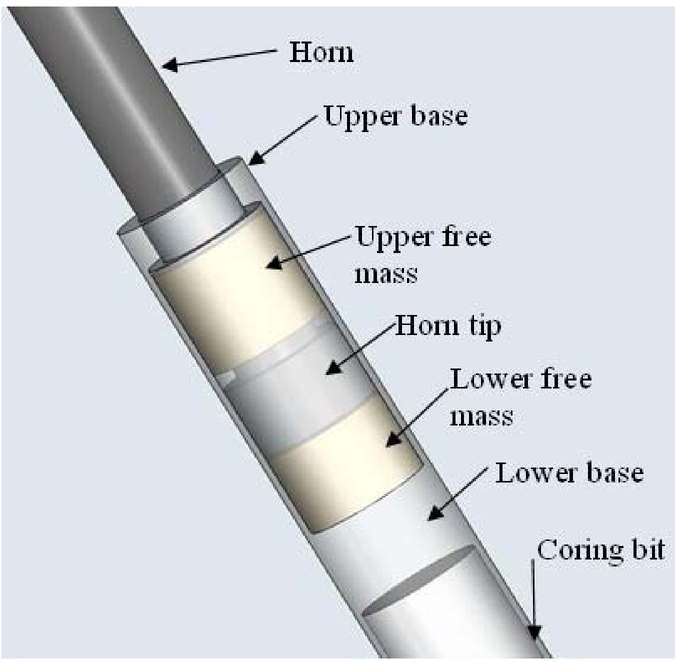


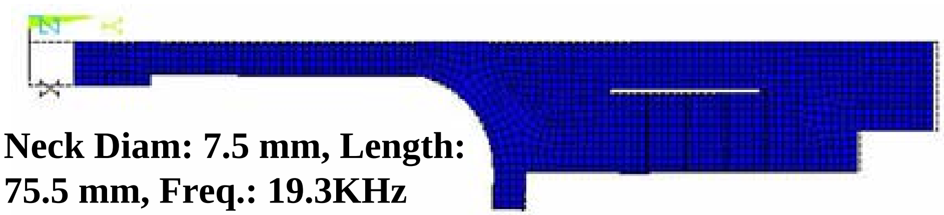


Ref: ASI's drawings

Dog-bone horn

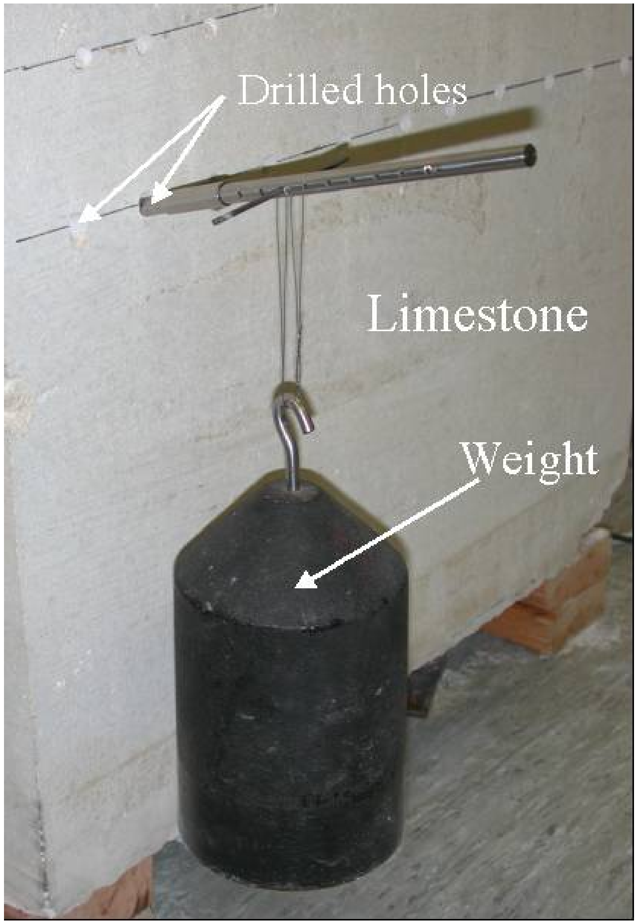
The dog-bone horn offers in addition to the performance enhancement also design benefits as a mounting fixture.

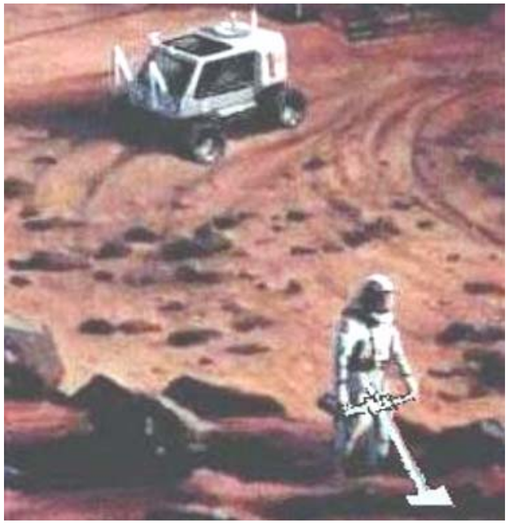




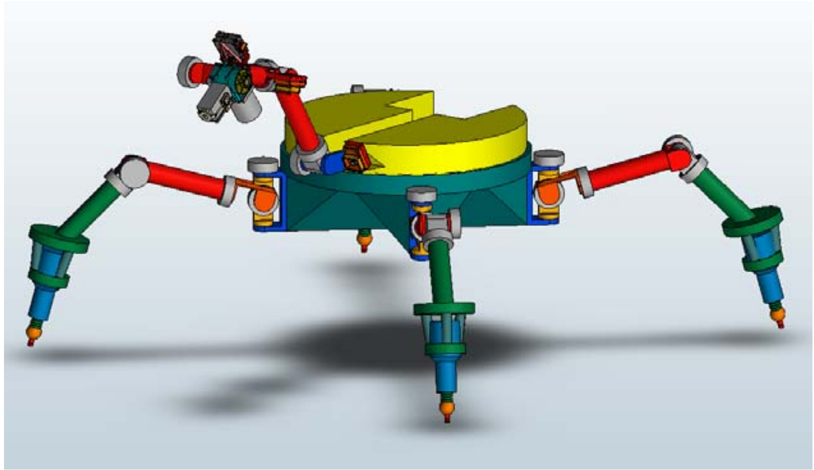
Neck Diam: 7.5 mm, Length: 75.5 mm, Freq.: 19.3KHz

U/S Anchor





Potential implementation

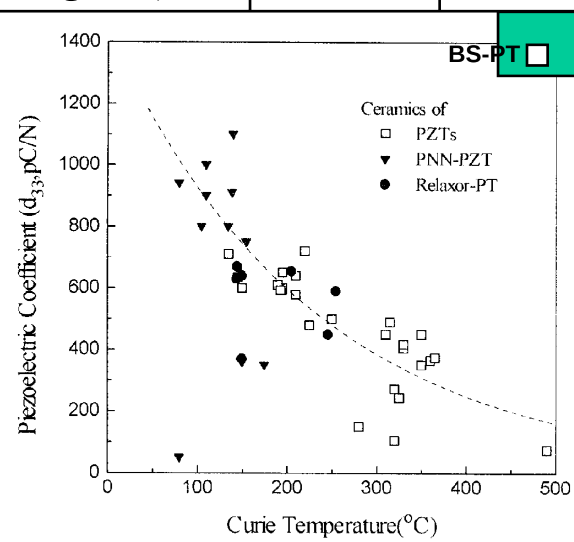


Steep Terrain Access Robot (STAR)

Operation in extreme environments

Comparison of various Piezoceramics with $BiScO_3–PbTiO_3$

Material	Structure	T_c (°C) (C/cm^2)	P_r	E_c kV/cm	d_{33} pC/N
PZT-5A (soft)	Perovskite (MPB)	330	36	~ 10–12	~ 400
PZT-8 (hard)	Perovskite (MPB)	330	25	> 15	~ 225
$PbNb_2O_6$ (modified)	Tungsten Bronze	~ 500	—	—	~ 85
$Na_{0.5}Bi_{4.5}Ti_4O_{15}$	Bismuth Layered	~ 600	—	—	18
$BiScO_3$– $xPbTiO_3$ x=62	Perovskite (rhombohedral)	420	28	17	290
$BiScO_3$– $xPbTiO_3$ x=64	**Perovskite (MPB)**	**450**	**32**	**21**	**465**
$BiScO_3$– $xPbTiO_3$ x=66	Perovskite (tetragonal)	460	23	25	260



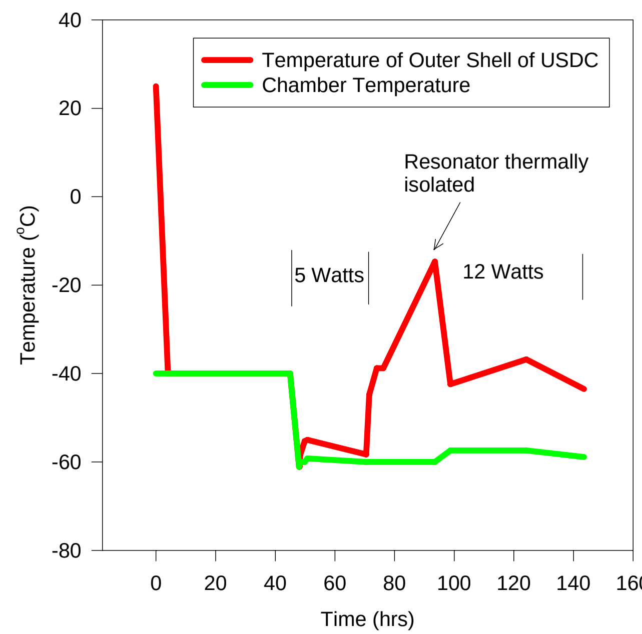
Ref: T. Shrout, Penn State U.

Preliminary tests of USDC at Low temperatures

Demonstrated drilling cold ice including: -40°C crashed ice, crashed ice with water and solid ice as well as -140°C in crashed ice and solid ice.

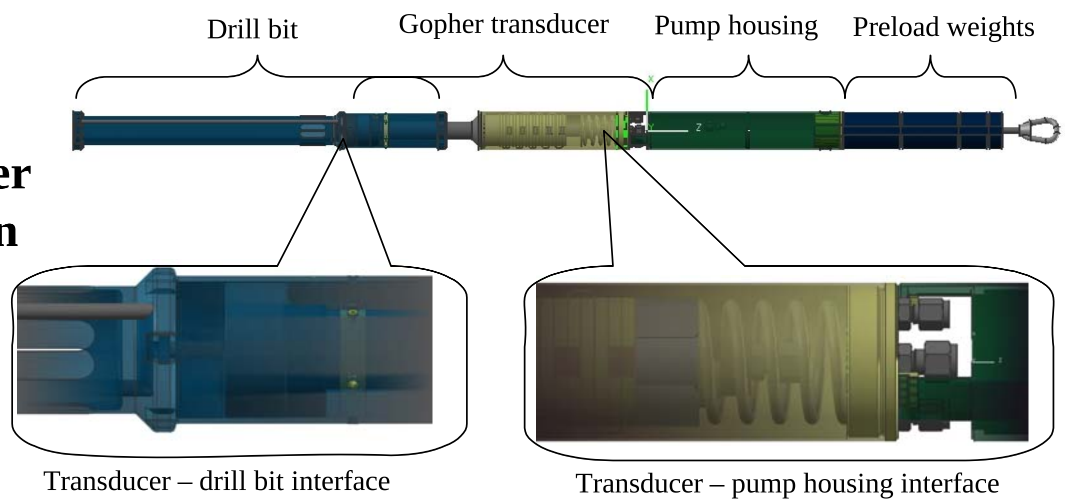
- **Crashed ice at -40°C and 140°C -** At both -40°C and 140°C no problem drilling and the speed was too fast to measure.
- **-40°C slush ice with water** - Drilled 7mm deep using 6-mm diameter drill in 1-minute.
- **-40°C solid ice -** About 1-cm in about 30-sec.
- **-140°C solid ice -** Cored about 3-mm deep using a 10-mm diameter
- **-40°C and -60°C** - Environmental testing for 160 hours

Tests were done at the JPL's Extraterrestrial Materials Simulation Laboratory.



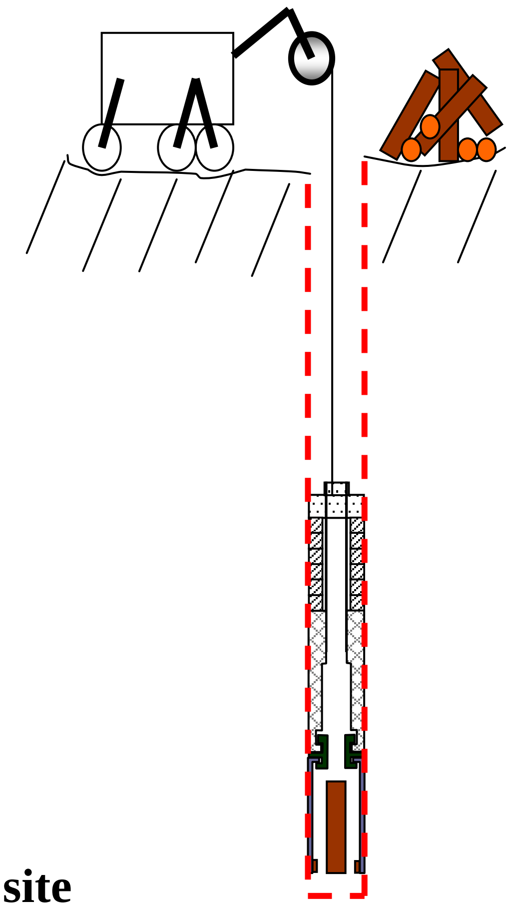
Gopher

Gopher design



Mt. Hood test site

Close up view of the drill site



A total of 1.25-m was accomplished in a total drilling of 5 hours with an average drilling of 0.25 m/hr.

Field test in Lake Vida, Antarctica

A total depth of 176cm was reached

Lake Vida test site.

Inside the drilling tent.

The gopher in the drilled hole

Use of Piezoelectric materials in flight hardware

- The heritage of using Electro-Mechanical Materials in space is documented on **http://eis.jpl.nasa.gov/ndeaa/nasa-mp/nasaonly/flight-hardware/piezo-in-space.htm**

- Currently, we are conducting a systematic study to support the use of piezoelectric stacks as actuators in SIM. The study involves
  - Assisting the definition of the requirements for the Specification Control Drawing (SCD) document,
  - Establishing credible life tests of piezoelectric stacks to determine degradation and catastrophic failures. For this purpose:
    - use qualification tests and screening
    - conduct parametric investigation of the mechanisms that cause damage to piezoelectric stacks.
  - Supporting the determination of the requirements for actuators procurement.

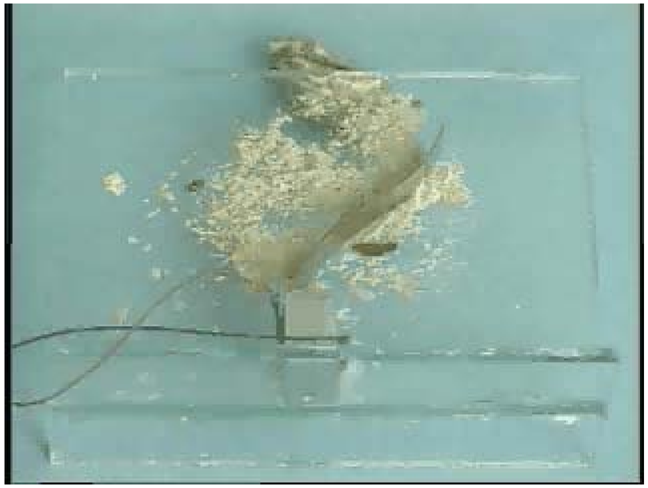
Electroactive Polymers (EAP) as Artificial Muscles

EAP - Background

- Most conventional mechanisms are driven by actuators requiring gears, bearings, and other complex components.
- Emulating biological muscles can enable various novel manipulation capabilities that are impossible today.
- Electroactive polymers (EAP) are emerging with capability that can mimic muscles to actuate biologically inspired mechanisms.
- EAP are resilient, fracture tolerant, noiseless actuators that can be made miniature, low mass, inexpensive and consume low power.
- EAP can potentially be used to construct 3-D systems, such as robotics, which can only be imagined as science fiction using such capabilities as inkjet printing.

Exploration of planetary applications

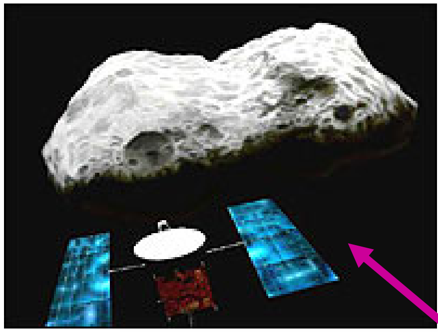
<u>Dust wiper</u>



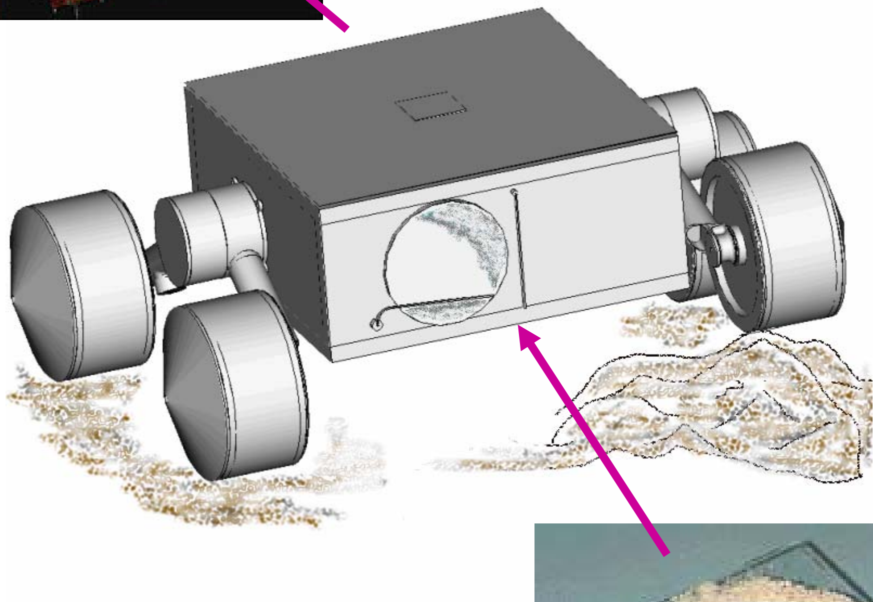
<u>Sample handling robotics</u>

EAP dust wiper

Baselined in the MUSES-CN Nanorover



MUSES-CN mission was a joint NASA and NASDA (National Space Development Agency of Japan) mission scheduled for launch in Jan. 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid. Due to budget constraints, this mission was cancelled in Nov. 2000.

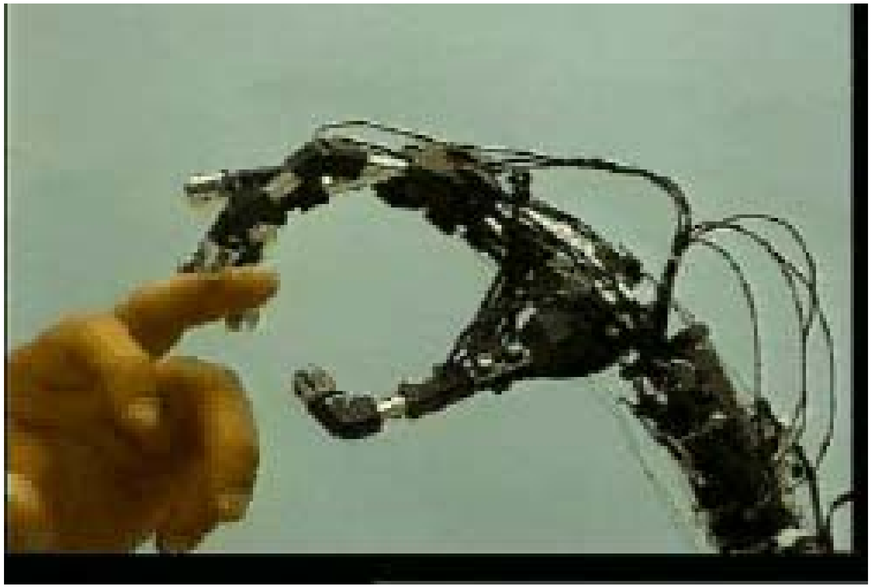


An EAP actuated wiper was selected as a baseline for the dust removal from the visual/IR window.

Platforms for EAP Implementation

Android making facial expressions

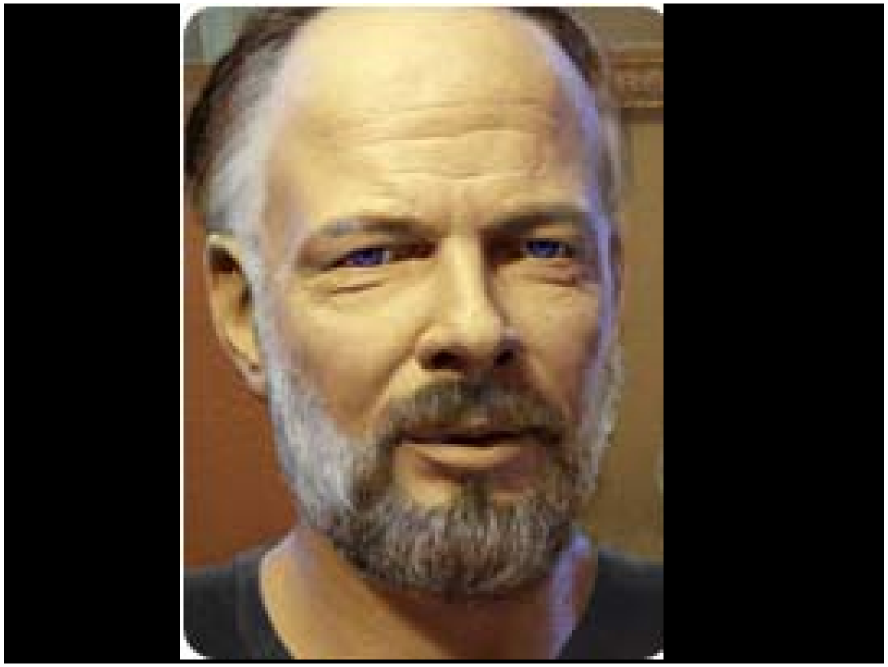
[Made by D. Hanson, U. of Texas, Dallas]



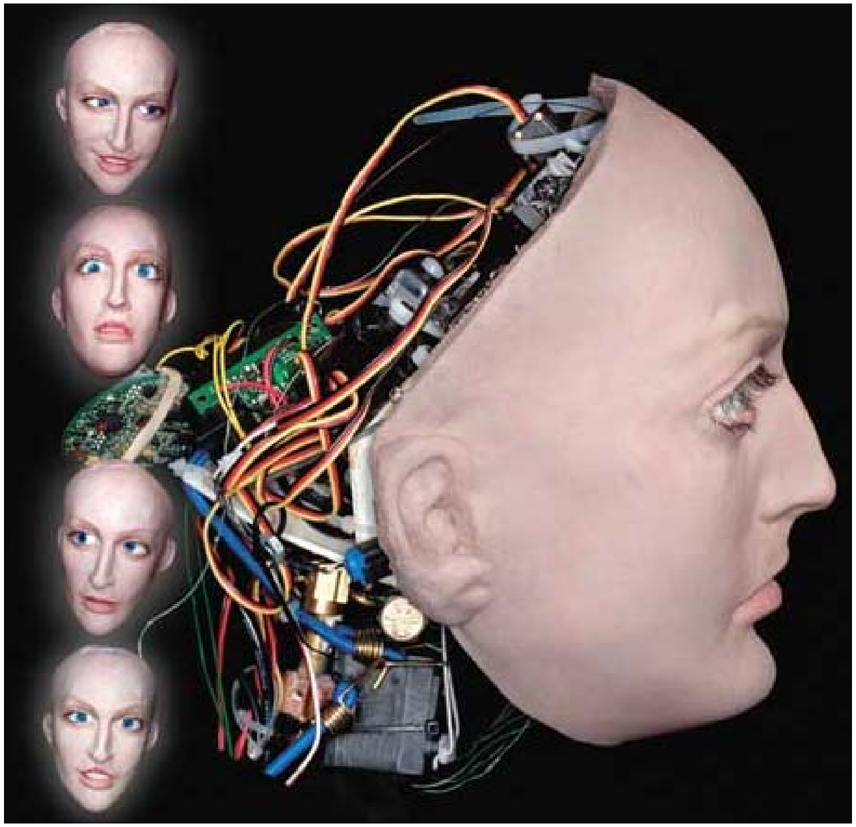
Robotic hand platform for EAP

[Made by G. Whiteley, Sheffield Hallam U., UK]

Android heads



Recent android portrait designed by David Hanson - America's science-fiction writers Philip K Dick (created the fiction behind Blade Runner and Minority Report and Total Recall).



Designed by David Hanson, who is a sculptor and engineer [Bar-Cohen, "Electric Flex," IEEE Spectrum, June 2004]

Video can be seen on: http://hansonrobotics.com/movies/sci_ch_NeXtFesT.asf

Courtesy of David Hanson

Full size robot with expressive head

- Humanlike head of Einstein (Hanson Robotics) and Hubo Robot body (KAIST) is the first ever expressive humanlike face on an untethered walking robot.
- This robot was made in celebrations of the 100 years anniversary of the theory of relativity.

Courtesy of David Hanson

The grand challenge for EAP as Artificial Muscles

Wrestling match between EAP actuated robotic arm and human

The performance of the human arm as a baseline for the development of EAP actuators

Background

In 1999, a challenge was posed to the worldwide research and engineering community to develop a robotic arm that is actuated by EAP to win an arm wrestling match against a human opponent.

- Initially, the challenge is to win against a human (any human) using a simple shape arm
- The ultimate challenge is to win against the strongest human using the closest resemblance of the human arm.

Objectives

- Promote advances towards making EAP actuators that are superior to human muscles
- Develop the infrastructure including: analytical tools, materials science, electromechanical tools, sensors, control, feedback, rapid response, larger actuation forces, actuator scalability (use of small and large ones), enhanced actuation efficiency, etc.
- Increase the worldwide visibility and recognition of EAP materials
- Attract interest among potential users and sponsors
- Lead to general public awareness – since they will end up being the users/beneficiaries

Current status

- John Brzenk (World Wrestling Champion), John Woolsey (ABC Worldwide wrist-wrestling Champion) and Harold Ryden (California State Champion) attended the 2004 EAP-in-Action Session and were introduced to the attendees to give them an idea about the toughness of this challenge.
- Competition judges were selected and rules were established for the competition.
- The United States ArmSports brought the competition table and provide 2 judges
- The first Armwrestling Match of EAP Robotic Arm against Human (AMERAH) was held on March 7, 2005 as part of the SPIE's EAPAD Conference.
- Three organizations brought their EAP actuated arms to compete
- The 17-year old student, Panna Felsen, won against all three arms

The First Arm-wrestling Contest

March 7, 2005

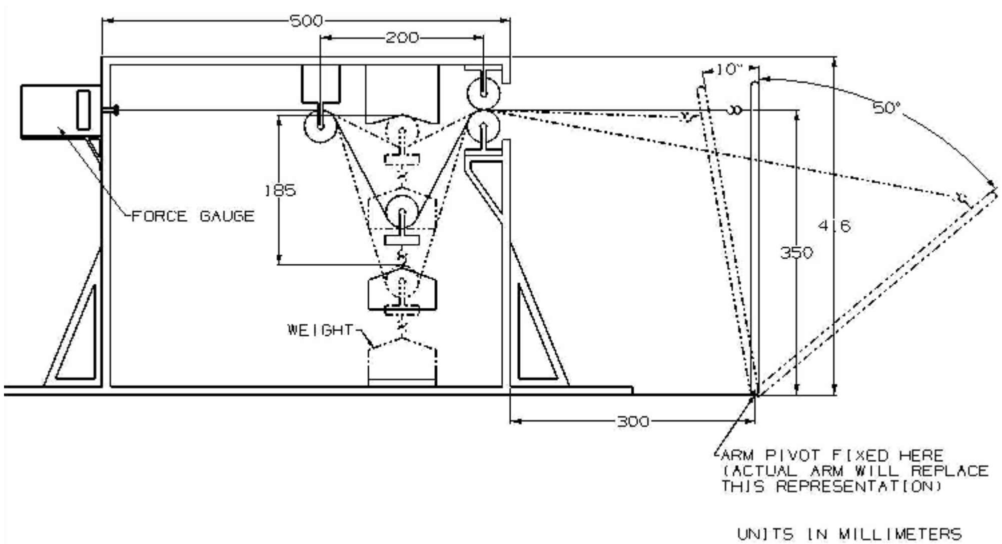
Environmental Robots Inc. (ERI), Albuquerque, NM, used dielectric elastomer and of ionic polymer metal composites (IPMC) strips – this arm lasted 26-sec.

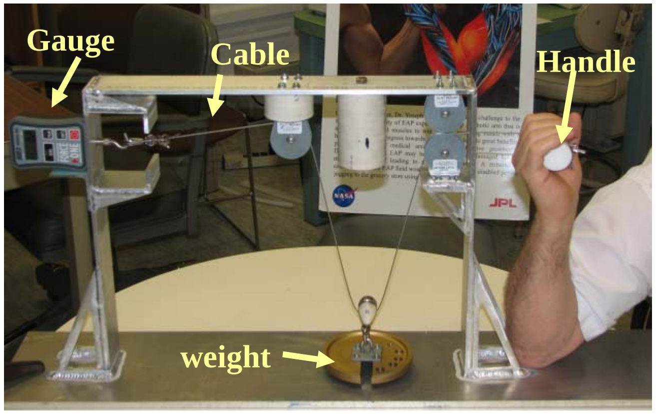
Students from VT used PAN gel fibers and an electrochemical cell – this arm lasted 3-sec.

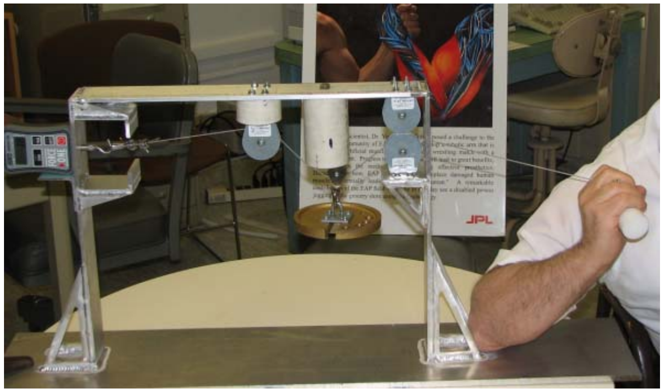
EMPA, Dubendorf, Switzerland used dielectric elastomer in 4 groups of multi-layered scrolled actuators– this arm lasted 4-sec.

The 2006 SPIE's EAPD competition

The competing arms will be measured for force and speed and will wrestle with each other to choose the strongest







Recent Progress

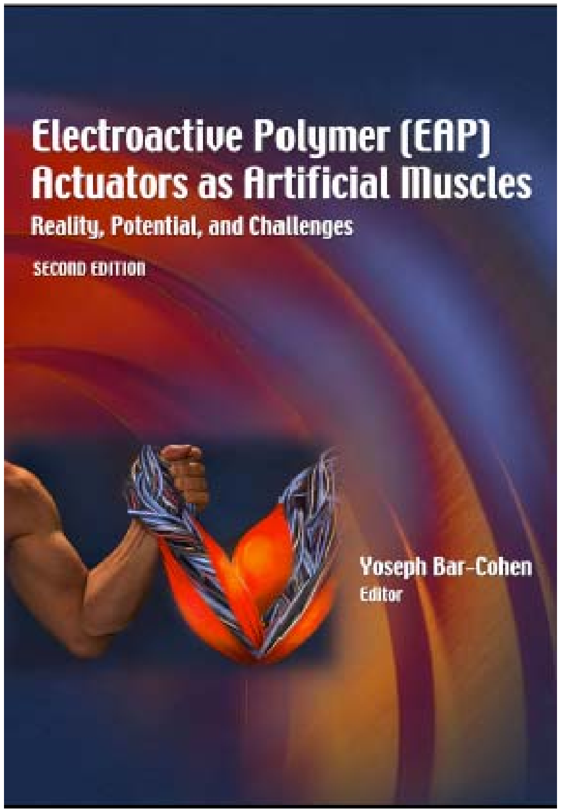
Dec. 2002- The first commercial EAP product - a fish robot (courtesy of Eamex, Japan)

Cover page of the Oct. 2003 issue

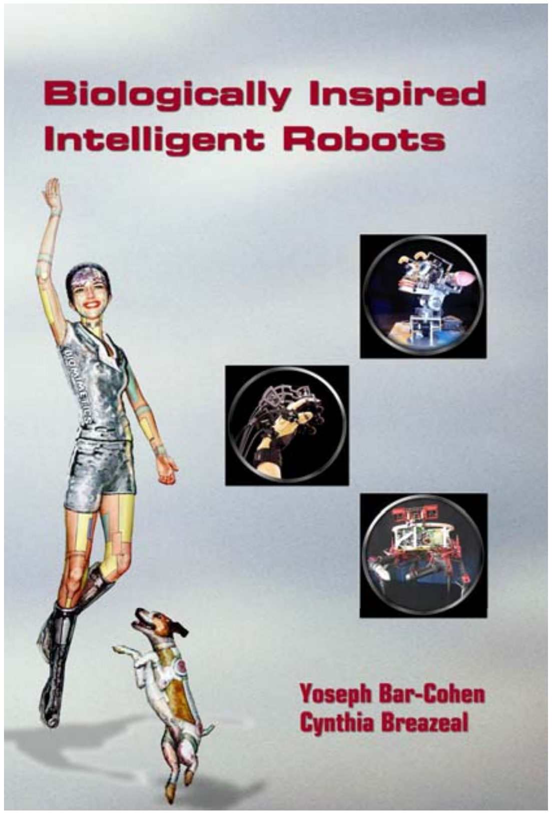
Dielectric elastomer EAP actuator made by SRI International

The first arm wrestling arm competition was held on March 7, 2005 and three different arms competed against a 17-year old student. The student won against all three where the strongest arm was the one made by Environmental Robots Incorporated (ERI), NM and it lasted 26-seconds.

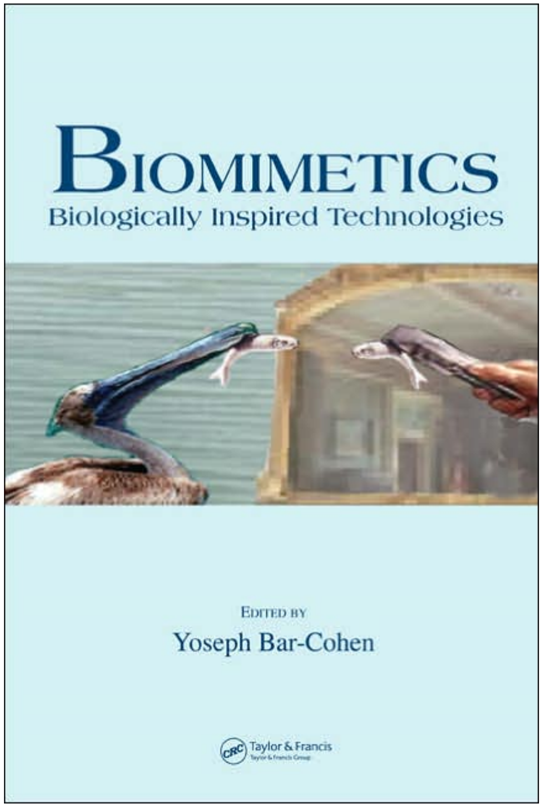
Related books



1st Edition (March, 2001)
2nd Edition (March, 2004)



May, 2003



October, 2005

http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm

Courtesy of David Hanson